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Spec Title: INDUCTION COOKER DESIGN WITH
CAPSENSE(R) - AN50475

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AN50475

Induction Cooker Design with CapSense®

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Abstract

AN50475 discusses the implementation of an induction cooker with CapSense® control based on CY8C22x45. The working principles of an induction cooker and the CY8C22x45 are also described.

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Introduction

Touch sensor technology has existed for many years because it is suitable for harsh environments. Capacitance based touch sensors are now widely applied in consumer electronics. Touch sensors appear stylish, and products based on touch sensors are attractive. In home appliances such as the microwave oven, induction cooker, and rice cooker, there is a growing demand for the CapSense button and slider for high-end designs. Typically, there are two microcontrollers in these designs: one for the kernel tasks control, and the other for the CapSense button/slider control. CY8C22x45 is a new PSoC product family that simplifies the design and reduces the system cost. This application note uses the induction cooker as an example to discuss the integration design of CapSense and system control in the CY8C22x45.

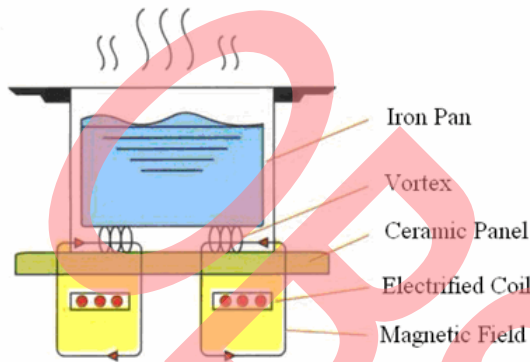
Induction Cooker: Working Principle

The induction cooker is a modern electric cooker that uses the electromagnetic induction principle to heat vessels. The induction cooker has a heatproof ceramic panel, which is used as the cooker plane. Through the electrified coil under the plane, the AC current creates a magnetic field that induces a vortex in iron and stainless steel pan bottoms. This heats the pan bottom quickly, and then conducts the heat to food.

This section describes the working principle of the induction cooker. First, the AC current is converted into DC by a rectifier. Next, the DC current is converted into ultrasonic high frequency AC current by a high frequency electric power conversion device. By connecting the high frequency AC current to the flat, hollow, helical heating coil, a high frequency alternating magnetic field is generated. Under the ceramic panel, the electrified coil creates a magnetic field that breaks through the panel and induces a vortex in the iron pan bottom. This converts

electric energy into heat energy, while overcoming the internal impedance stream. The generated joule heat is the heat source for cooking.

Figure 1. Induction Cooker



The major controls of the induction cooker include:

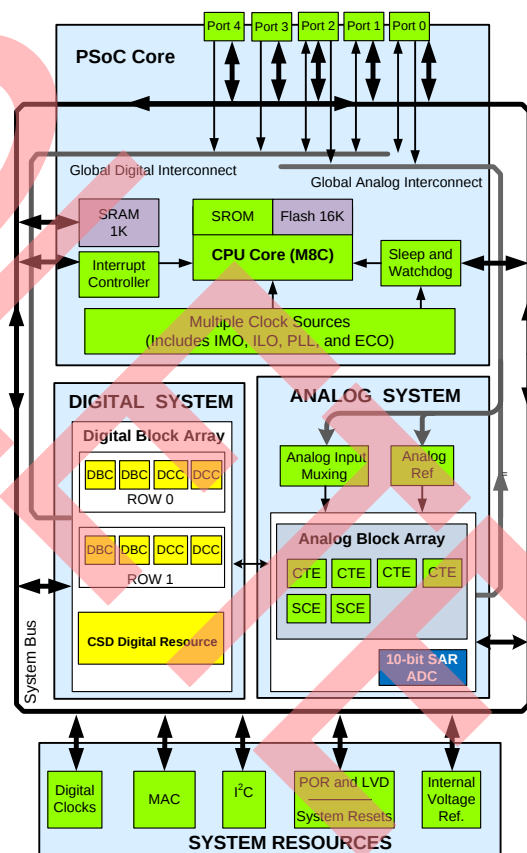
1. **IGBT Automatic Self Protection:** Insulated-Gate Bipolar Transistor (IGBT) is the key component of the induction cooker. IGBT works under high voltage and high power conditions. However, considering the high cost and rigid parameters, IGBT is designed with several conditions. Any of the following factors can destroy IGBT: excess voltage, instantaneous impingement generated when power is switched on or off, proliferated current and excess temperature. IGBT can be damaged even when the iron pan is removed from the ceramic panel or if no pan is placed on the panel. It is necessary to protect the IGBT from these factors.
2. **Temperature Control in the Iron Pan Bottom:** The heat in the iron pan bottom is directly transferred to the ceramic panel. The ceramic panel is the heat conducting material, so thermal sensors are often fixed in the panel bottom to detect the temperature of the iron pan bottom.
3. **Stable Power Control:** The output power of the induction cooker can be automatically regulated to improve the adjustment of the power supply and load.
4. **User Interface Control:** Collect the customer input from the CapSense button or slider, then decide the working mode and display it on relevant light emitting diode (LED).

In this example, CY8C22x45 handles the input of twelve CapSense buttons. It is also responsible for the entire system control, including current, voltage and temperature sampling, PWM generation for the MOSFET control, induction cooker power control, and system status display.

CY8C22x45 Overview

CY8C22x45 is a product of the PSoC family. It is an enhancement of CY8C21xxx PSoC family, and is targeted at applications that integrate both system control and CapSense control. CY8C22x45 is compatible with other PSoC device architecture, as shown in Figure 2. CY8C22x45 is a Mixed-Signal Array with On-Chip Controller device. Each CY8C22x45 PSoC device includes eight digital blocks and six analog blocks. Depending on the PSoC package, CY8C22x45 provides up to 38 general-purpose I/Os (GPIO), 16 K flash memory, and a 1 K SRAM data memory. Following other PSoC products, CY8C22x45 has fixed function on-chip resources such as I²C, MAC, and more. In addition, CY8C22x45 includes optimized modules such as 10-bit SAR ADC, dedicated CSD digital logic, and dedicated RTC.

Figure 2. CY8C22x45 Block Diagram



To reflect the change in digital blocks, the new digital block for basic functions is renamed as DBC from DBB, and the communication block is renamed as DCC. The digital block adds another data path to implement the enhanced features in DBC or DCC, such as synchronous triggering, kill function, and more. However, even if no

enhanced feature is used in the user module, the digital block is fully compatible with the existing PSoC product.

Compared to CY8C21xxx, CY8C22x45 provides two additional CT blocks for general-purpose applications. These analog blocks can be configured as an enhanced feature comparator with flexible input and output choices.

CY8C22x45 also provides a set of digital resources to address the CapSense design. These resources are optimized for CSD implementation. With these resources, the system clock resource VC1/VC2/VC3 and digital blocks are not needed to configure a CSD user module. The CY8C22x45 also keeps a compatible configuration, which helps the customer code migrate from CY8C21xxx. The new CSD user module in CY8C22x45 is capable of simultaneous scanning on dual CSD channel input to reduce the total scanning time in an application.

System Features

In addition to the features that CY8C22x45 provides for CapSense control, the induction cooker design also contains the system control. It has common features that are found in existing products. The features are:

- AC 220 V/50 Hz power supply
- 1800 W rated power
- Resonant circuit for induction cooker control
- More than ten LEDs and four digital LED segment display
- Buzzer for alarm
- Fan On/Off and PWM control
- Adjustable fixed temperature cooking mode that Supports 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, and 260 °C.
- Multilevel of firepower selection (200 W, 400 W, 600 W, 800 W, 1000 W, 1200 W, 1400 W, 1600 W and 1800 W) and Stable Power Control
- Cooking Pan Auto Detect
- Multi Cooking Mode Selection
- Multiple protection
 - ❑ Auto Power Off When Not Cooking on Pans
 - ❑ AC Over Voltage and Under Voltage Protection
 - ❑ AC Over Current Protection
 - ❑ Pan Overheat Protection
 - ❑ IGBT Overheat Protection
- Time-switch cooking function

- 12 CapSense buttons for Menu Selection

More advanced CapSense features are to be included in future designs. These functions include:

- CapSense Slider for Menu Selection
- Waterproofing CapSense button
- Boil over detection
- CapSense sensor failure detection

System Hardware

There are two PCB boards in the design viz. power control board and main controller board. They are connected by an 11-pin ripple cable.

Power Control Board

The power control board uses a quasi resonant converter to create a magnetic field that induces a vortex in iron and stainless steel pan bottoms. Figure 3 shows a typical quasi resonant converter, Figure 4 shows the equivalent of the resonant circuit, and Figure 5 shows the waveforms of each block of the main power circuit in a cycle.

Figure 3. Quasi Resonant Converter

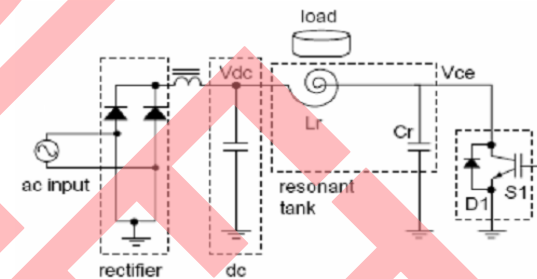


Figure 4. The Equivalent of the Resonant Circuit

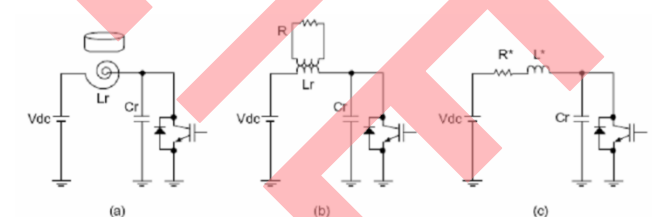
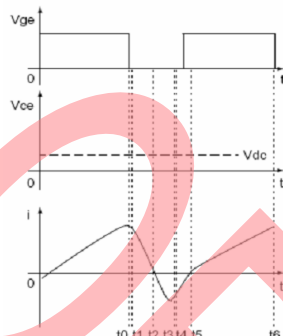
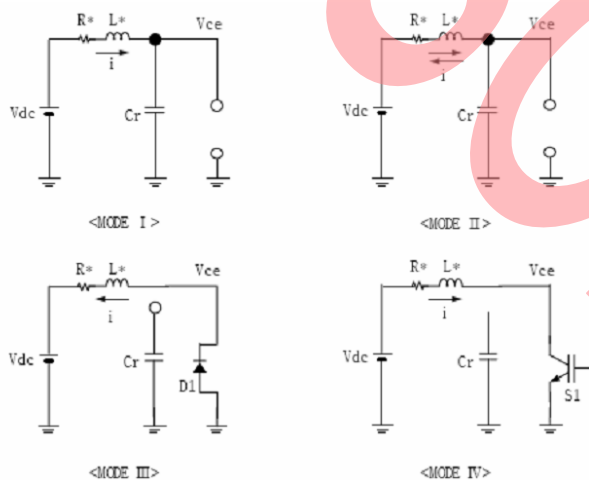


Figure 5. Waveforms of Each Block of the Main Power Circuit in a Cycle



- Initially, S1 is turned off by the control circuit when the current flowing through L^* and S1 reaches its peak.
- At this point, $V_c(0) = 0$ V. There are four modes available, as shown in Figure 6.

Figure 6. Modes in Quasi-Resonant Converter



MODE I: t0-t1

- The switching circuit is turned off when the resonant current flowing through the circuit is at its peak, i.e. at t_0 . In this process, a turn-off switching loss occurs. The V_{ce} level is rapidly increased by the capacitor (Cr) to become DC-LINK (V_{dc}) at t_1 .
- Even when the switch is turned off at t_0 , the current keeps incrementing to reach its peak at t_1 , when V_{ce} becomes equal to V_{dc} , as DC-LINK is higher than the resonant voltage. At this point, the energy stored in the inductor begins to be transferred to the capacitor.

MODE II: t1-t4

- As V_{dc} is lower than V_{ce} after t_1 , the current decreases to zero at t_2 , when the resonant voltage reaches its maximum. This is also the point where the transfer of the energy stored in the inductor to the capacitor is completed. The peak level of the resonant voltage has a direct relationship with the turn-on time of the switch (MODE IV: t_5 - t_6).
- After t_2 , the capacitor starts discharging the energy to the inductor, which causes the voltage and the current flowing in inverse to decrement and at t_6 , the switching circuit is turned off, returning to MODE I. As the peak level of the voltage is in direct relationship with the on-duty frequency, one can manipulate this level, i.e. output energy, by adding or reducing the on-duty frequency. Reach its minimum level at t_3 , i.e. $V_{ce}=V_{dc}$, respectively. Passing t_3 , the resonant current increases as $V_{ce}<V_{dc}$ and the discharge is completed at t_4 .

MODE III: t4-t5

- After t_4 , the energy sent by the capacitor and stored in the inductor, is converted to DC-LINK as the D1 diode is forward biased. The resonant current is flowing through D1 during the time S1 is turned ON.

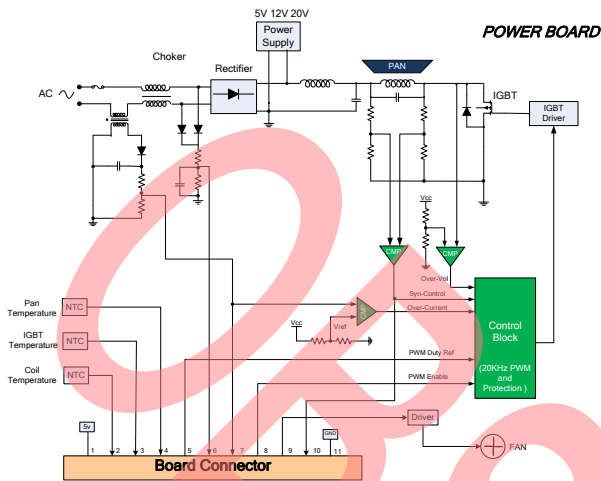
MODE IV: t5-t6

- As the switching circuit remains turned on while the current is freewheeling through D1, the current flows in the right direction through the circuit and the inductor starts to store the energy, which makes it possible to do a zero voltage turn-on switching.
- At t_6 , the switching circuit is turned off, returning to MODE I. As the peak level of the voltage is in direct relationship with the on-duty frequency, one can manipulate this level, i.e. output energy, by adding or reducing the on-duty frequency.

From the above description, we can understand that the peak current produced i.e. power delivered to the pan by means of induction depends on duty cycle of the IGBT PWM.

The power control board is close to the electrified coil on the bottom of the cooker. It includes the AC power input rectifier, choke, IGBT for DC/AC conversion, the zero-voltage switching control circuit for IGBT, current sensing and other high voltage components, DC power supply, fan and buzzer driver, and more. Figure 7 shows the block diagram of the power module board. All the components on this board are discrete components.

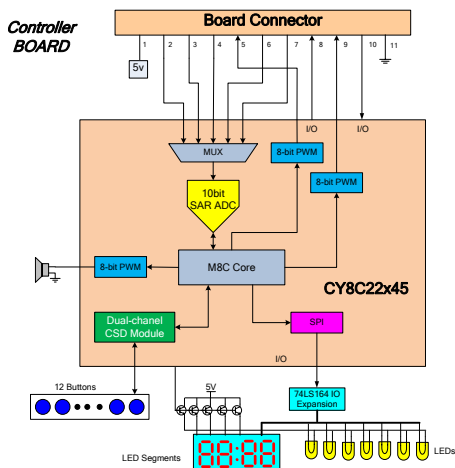
Figure 7. Power Control Board



Main controller board

The second PCB board is the main controller board based on CY8C22x45. This board is responsible for system control and user interface control, and the board is mounted on the top side of the cooker. This board handles the scanning of CapSense buttons and the LED displaying control. It is also responsible for the entire system control, including current, voltage, and temperature sampling, generating PWM duty cycle for the induction cooker power control, over-current, over voltage, and over temperature protection, menu operation control, and system status display. A real-time clock provided by CY8C22x45 is also applied for the timer in the cooker. Figure 8 shows the block diagram of the main controller board.

Figure 8. Main Controller Board



Dual-Channel CapSense Scan

Dual-channel CSD scanning is a new feature of CY8C22x45. It has the following advantages over the old CSD logic:

- The dual-channel CSD logic does not consume any digital block resource.
- It has two separated CSD logic and can support dual-channel CSD scan.
- Dedicated clock resource frees the VC1/VC2/VC3 clocks for other system control.
- M8C needs to respond to only one interrupt for each CapSense button scan.

Figure 9. Block Diagram of CSD2X

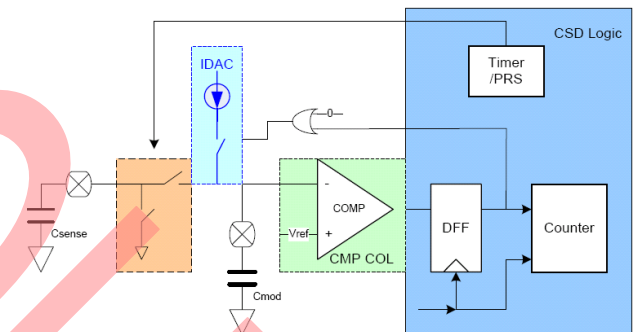
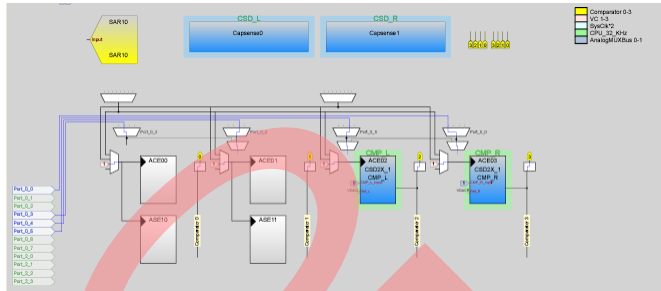


Figure 9 shows the block diagram of a single channel CSD in CY8C22x45. An internal IDAC is used to charge the external capacitor Cmod. The value in counter represents the duty the IDAC is turned on. The counter data increases with the capacitance of CapSense. The clock to drive IO_MUX can be fixed frequency clock or PRS output to reduce the EMI and noise effect. The Vref comes from Vbg or VDAC. Digital blocks and VC1/VC2/VC3 are not used, and they are free for other customer functions, for example, UART or SPI.

When the user module runs, only one interrupt can happen at the end of the scan. This allows the CPU to release more MIPS, and allows multisource interrupts. The analog bus is split into two separate sections: left analog bus and right analog bus. As a result, it can simultaneously support dual-channel CSD scan.

The dual-channel CSD user module consumes only CSD logic, two analog columns, left and right analog bus, and dual-channel IDAC. The following figure shows the consumption.

Figure 10. Resource of CSD2X



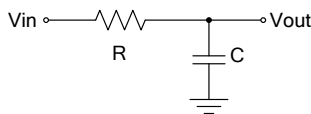
I/O Expansion by 74HC164

I/O expansion is necessary in many home appliance applications. Typically, a serial-parallel converter logic chip, such as 74HC164, is applied to the system for LED control. 74HC164 are 8-bit edge-triggered shift registers with serial data entry and output from each of the eight stages. As a result, the system can consume less I/Os than the solution that drives the LED directly. The input signals of 74HC164 are Data and Clock. This is in compliance with the SPI bus. See the Appendix Board Schematics (Figure 16 and Figure 17) for more information.

Low-Pass Filter for Analog Signal

There are four analog signals in the control board. They are all voltage signals, including the AC RMS voltage, AC average current, and the temperatures of the pan and IGBT. The range of these signals is from 0 to 5 V. Because these signals are the output from the noise power board, a capacitive low-pass filter is designed before the signal enters PSoC. Figure 11 shows the typical circuit.

Figure 11. Capacitive Low-Pass Filter



The cutoff frequency is:

$$f_{\text{cutoff}} = 1/2\pi RC \quad \text{Equation 1}$$

In Equation 1, assuming the value of R is 47 kΩ and the value of C is 0.1 μf, then the circuit gets a cutoff frequency at 33.9 Hz. This is because these signals change very slowly, especially the temperature signals of the pan and IGBT. The parameters of this capacitive low-pass filter can meet the system design requirement.

Board Connector Definition and Description

The following table indicates the board connector definition and description.

Table 1. Board Connector Definition

Pin	Type	Description
1	Power	Power Supply of 5 V
2	Analog Input	Temperature of Coil
3	Analog Input	Temperature of IGBT
4	Analog Input	Temperature of Pan
5	Digital Output	PWM Output Signal for Power Control
6	Analog Input	AC RSM Voltage
7	Analog Input	AC Average Current
8	Digital Output	PWM Output Enable Signal
9	Digital Output	Fan Output
10	Digital Input	Zero-crossing Signal of Resonance Circuit.
11	Ground	Ground

System Firmware

The system firmware is relatively complicated. Because the system functions include the user interface control, such as the CapSense button scan and LED display, it also includes the analog signals sampling and internal timer. In addition, the control algorithm implementation such as fixed temperature control algorithm, stable power control algorithm, multiple protections, and induction cooker kernel functions are also included. Figure 13 shows the high-level flow chart of the firmware.

For each cooking mode the firmware uses either constant temperature or constant power. For both power or temperature control, the ON time of the IGBT PWM is controlled. A PI controller is used for the same which is explained in the section “PI Close Loop Control Algorithm”.

When the pan is placed on the cooker top, the inductance of the resonant converter (L*) is increased. This effectively decreases the switching frequency. The sync control signal shown in Figure 11 is the zero crossing signal of the resonant converter voltage. The sync control pulses are counted for a fixed period. Thus the number of sync control pulses would thus be less when the pan is present compared to when the pan is absent. If the Pan is not present the IGBT is turned OFF.

The CT is used to measure the current from the AC mains. We limit the IGBT PWM maximum duty cycle such that the peak current is less than 10 A.

The temperatures sensors are used to measure PAN, IGBT and Coil temperature. The limiting values for PAN, IGBT and Coil temperatures are 300, 80, and 80 °C.

Fan is used to cool the IGBT and quasi resonant converter coil. PWM signal for driving the fan is generated by the Main controller board.

Figure 12. Power Board

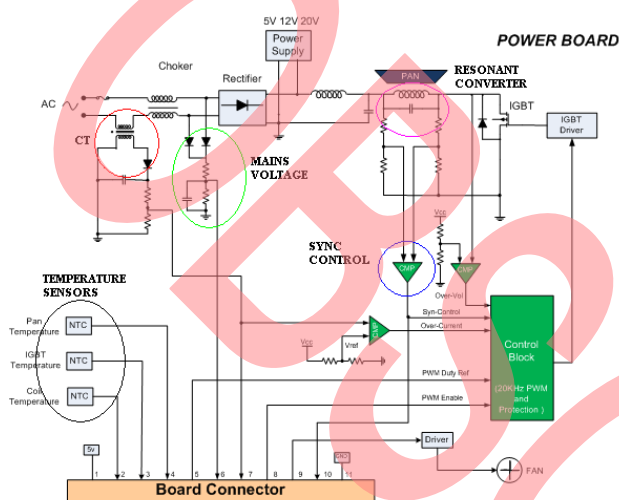
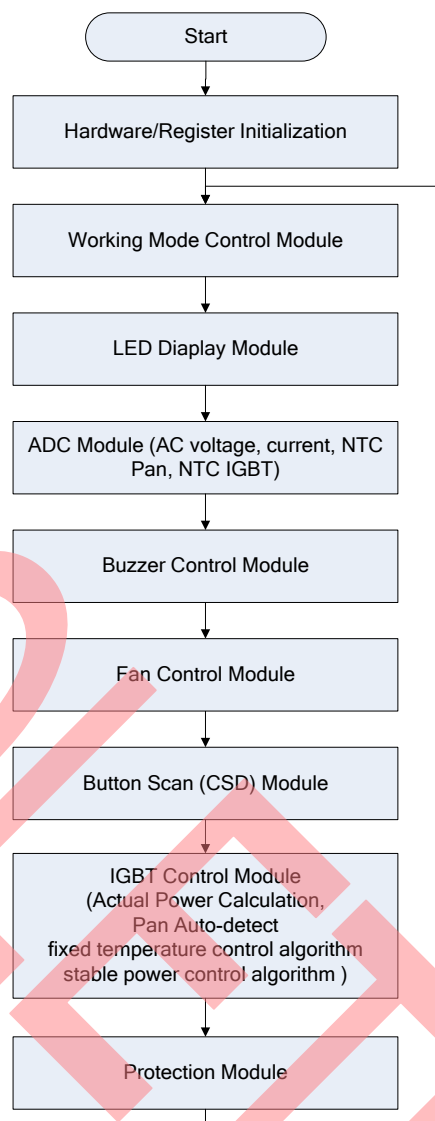


Figure 13. Flow Chart of Firmware



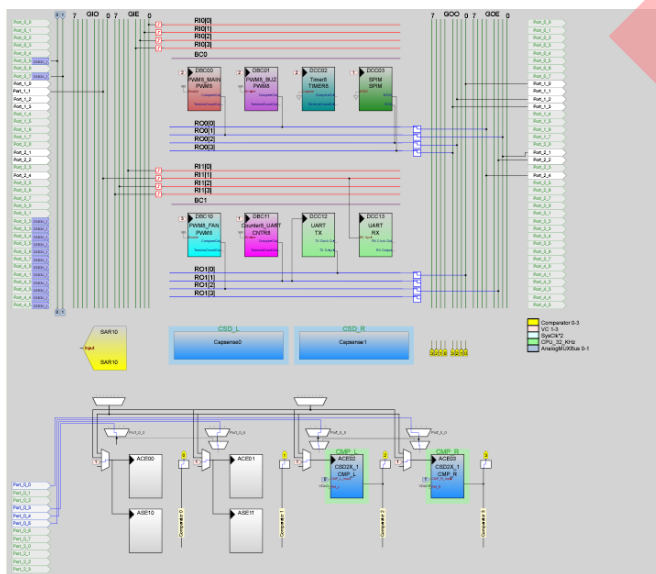
PSoC Digital Block and Analog Resources Consumed

The following table lists the digital blocks, analog blocks, and other resources consumed in the induction cooker system.

Table 2. PSoC Digital Block and Analog Resources

Name	Description
DBC00	PWM8 for IGBT power control
DBC01	PWM8 for buzzer control
DCC02	Timer8 for internal click
DCC03	SPIM for 74HCT164 driving
DBC10	PWM8 for fan control
DBC11	Counter8 for UART clock (Optional)
DCC12	UART TX for system debug (Optional)
DCC13	UART RX for system debug (Optional)
ACE02	Used be CSD2X for button scan
ACE 03	Used be CSD2X for button scan
CSD2X	Button scan
RTC	System timer
SAR10	Analog signals sampling

Figure 14. System Interconnection



LEDs and 7-Segment Digital LED Display Refresh

The user interface of the induction cooker is important, because the end user exchanges all information through it. In the design, the 74HC164 is used to expand the I/O to drive the four 7-segment LED display. Any delay in refreshing results in the blinking of the LED. So an 8-bit timer is used in the firmware, and the interrupt of the timer requests the LEDs to be refreshed. A display buffer, whose value is set in main loop, is also used to refresh The LEDs. In the Timer8 IRQ, the contents of this buffer are sent out through the SPI user module, which is cascaded with the 74HC164 for LED driving. The LEDs are grouped by 6, and each group is turned on in sequence. The scan interval is set as 2 ms or 3 ms, so the refresh rate is around 55 Hz to 83 Hz.

The following firmware shows the scan of the LED display:

```
BYTE baLedBuf[6];
// display buffer
```

The refreshing code in the Timer8 IRQ is:

```
void Timer8_ISR( void )
{
    static BYTE bLedTimer;
    wTick++;
    // global for tick

    if( wTick - bLedTimer > LEDONTIME )
    // period is 2ms
    {
        bLedTimer = wTick;
        bComInx ++;
        if( bComInx>=LEDCOMNUM)
            bComInx = 0;
        switch( bComInx )
        {
            case 0:
                LED_COM5_OFF;
                SPIM_TX_BUFFER_REG =
baLedBuf[0];
                LED_COM0_ON;
                break;
            case 1:
                LED_COM0_OFF;
                SPIM_TX_BUFFER_REG =
baLedBuf[1];
                LED_COM1_ON;
                break;
            case 2:
                LED_COM1_OFF;
                SPIM_TX_BUFFER_REG =
baLedBuf[2];
                LED_COM2_ON;
                break;
            case 3:
                LED_COM2_OFF;
```

```

        SPIM_TX_BUFFER_REG =
baLedBuf[3];
        LED_COM3_ON;
        break;
    case 4:
        LED_COM3_OFF;
        SPIM_TX_BUFFER_REG =
baLedBuf[4];
        LED_COM4_ON;
        break;
    case 5:
        LED_COM4_OFF;
        SPIM_TX_BUFFER_REG =
baLedBuf[5];
        LED_COM5_ON;
        break;

```

IIR Low-Pass Digital Filter

The digital filter is widely used in the control. However, not all digital filters can be implemented on the PSoC, because many digital filters need enhanced MAC units to speed the calculation. In this system, a simple one order IIR low-pass digital filter is introduced, and the IIR filter is used for all analog input signal processing. The algorithm is shown in the following formula.

$$y_n = a * x_n + (1 - a) * y_{n-1} \quad \text{Equation 2}$$

In Equation 2:

a is the filter coefficient.

x_n is the current sampling value.

y_n is the current output of filter.

y_{n-1} is the last output of filter.

To finish the calculation, the multiplication and addition operations need two times. Considering the PSoC CPU resources, the calculation is still complicated. To achieve the low-pass filter and simplify this algorithm, the special filter coefficient is required. For example, using $a = 0.25$, the following formula is obtained:

$$y_n = 0.25 * x_n + 0.75 * y_{(n-1)} \quad \text{Equation 3}$$

Replacing multiplication operation with bit-shifting operation, the formula can be changed to:

$$y_n = x_n \gg 2 + y_{(n-1)} \gg 1 + y_{(n-1)} \gg 2 \quad \text{Equation 4}$$

With this equation, only three bit-shifting operations and three addition operations are need for the calculation. In this system, the value of a is 0.25. The cutoff frequency of this filter is 1.33 Hz, according to the following formula with a sampling period of 40 ms.

$$f_{\text{cutoff}} = a / 2\pi T(1-a) \quad \text{Equation 5}$$

In Equation 5, T is the sampling period.

PI Close Loop Control Algorithm

The induction cooker can support fixed power cooking and fixed temperature cooking modes. PI close loop control is applied in both the fixed power cooking mode and the fixed temperature cooking mode. The PI control algorithm is very useful in a continuous control system. There are two basic PI control algorithms: absolute mode and increment mode PI control algorithm. The following equation is a discrete expression of the position mode of the PI algorithm.

$$u_k = K_P * e_k + K_I * \sum_{i=1}^{(k-1)} e_i + u_0 \quad \text{Equation 6}$$

In Equation 6:

e_k is power error.

K_I is the integration coefficient.

K_P is the proportional coefficient.

Another mode of PI algorithm is the increment mode, and the formula is:

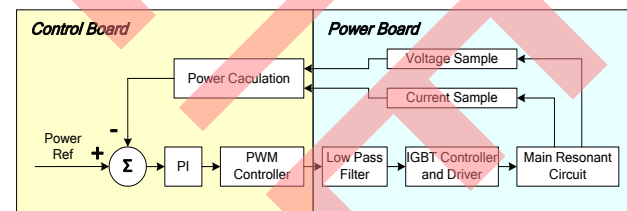
$$\Delta u_k = u_k - u_{(k-1)} = K_P * (e_k - e_{(k-1)}) + K_I * e_k \quad \text{Equation 7}$$

Compared to the absolute mode PI algorithm, the increment mode PI algorithm has the following advantages:

- There is no accumulation using this formula, and the result can be obtained by the last two sample values.
- The output of this formula is the increment value, and with firmware protection there is less chance for errors.
- The complexity of increment mode PI algorithm is less than that of absolute mode. It can save more PSoC system resources.

Figure 15 shows the block diagram of PI algorithm power control for fixed power cooking mode.

Figure 15. Block Diagram of PI Algorithm Power Control



The PWM output is the control signal of the main resonant power. Through a low-pass filter in the power control board, a reference voltage is achieved. The reference voltage is the input signal of IGBT control logical circuits, which has functions of pulse generation, synchronization, protection and IGBT driver. The main resonant circuit output increases with the reference voltage. As a result, the induction cooker power can be adjusted by changing the duty of PWM.

If the induction cooker works in fixed power cooking mode, the close loop is implemented in the following steps: sample RSM value of voltage and RSM value of current of main resonant circuit; calculate current power; compare with reference power and get error; adjust the duty of the PWM output according to the PI algorithm.

Summary

This application note describes induction cooker control system based on PSoC chip CY8C22x45. With the assistance of PSoC device, all the functions of the control board can be integrated into one chip. With few external components and optimized algorithm, this design incorporates all the kernel functions of the induction cooker, CapSense button scan, stable power close loop control, and fixed temperature close loop control.

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Appendix A

Figure 16. Board Schematic

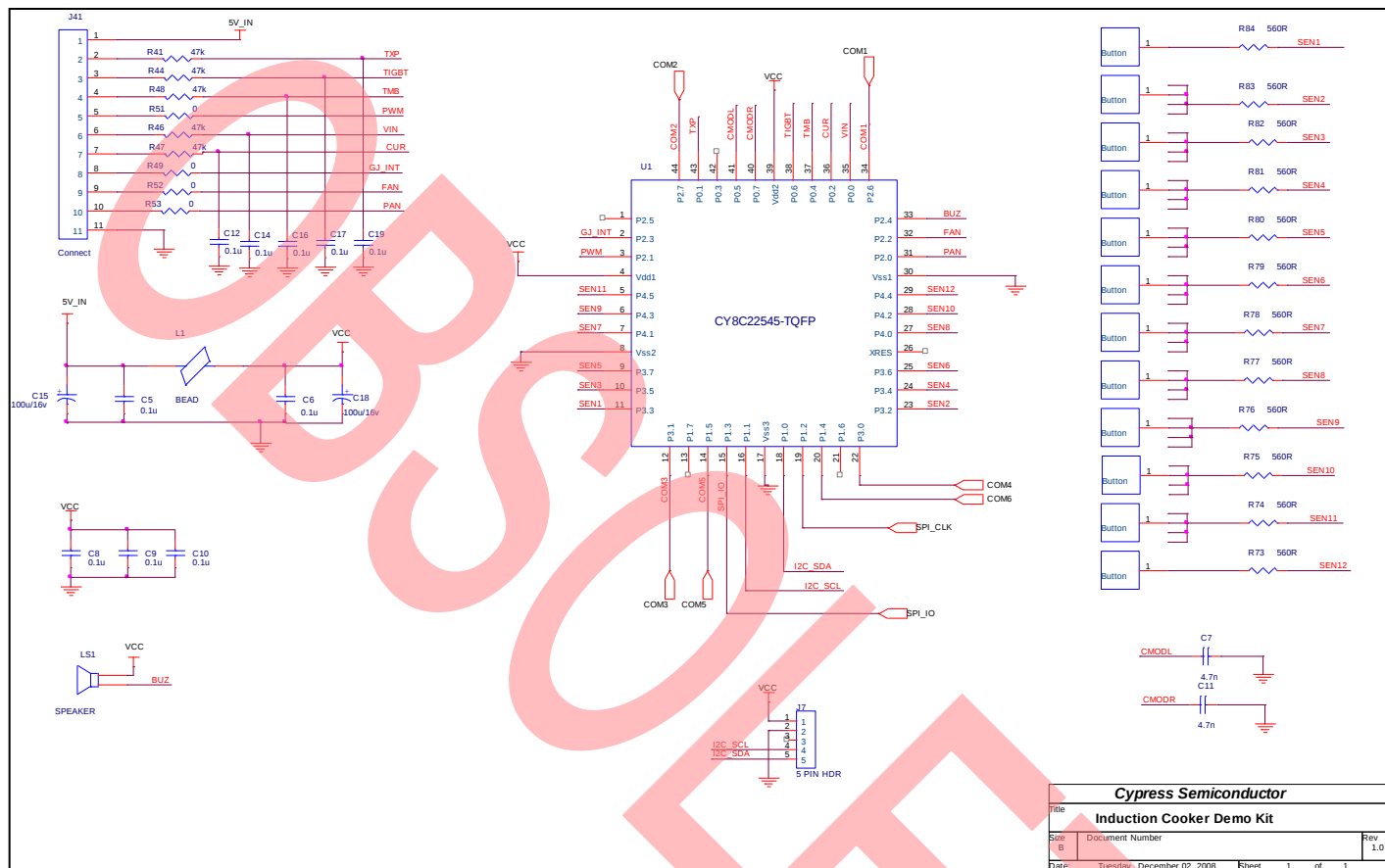


Figure 17. Schematic Drawing of Induction Cooker Evaluation Kit

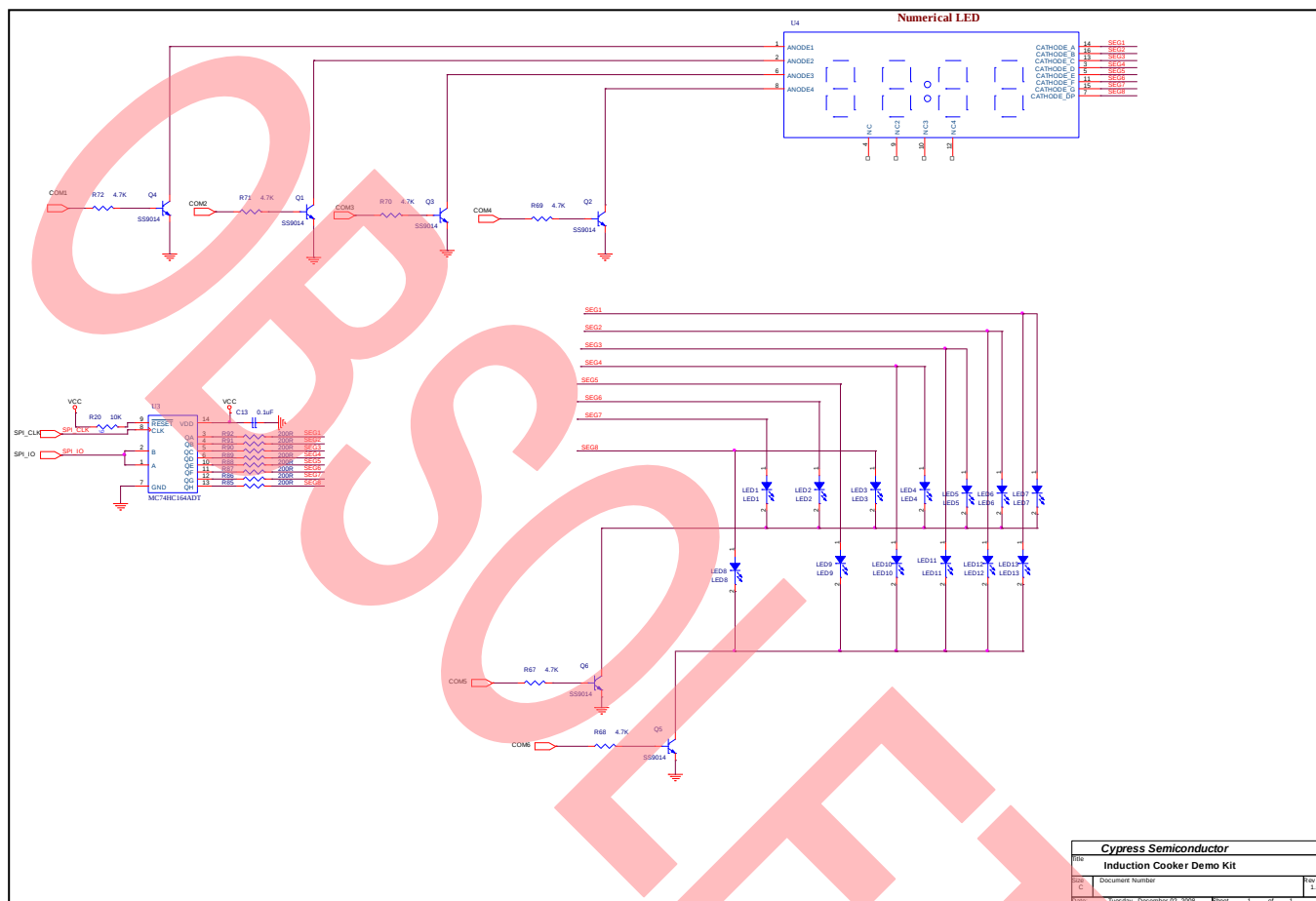


Figure 18. Photograph of Induction Cooker Evaluation Kit

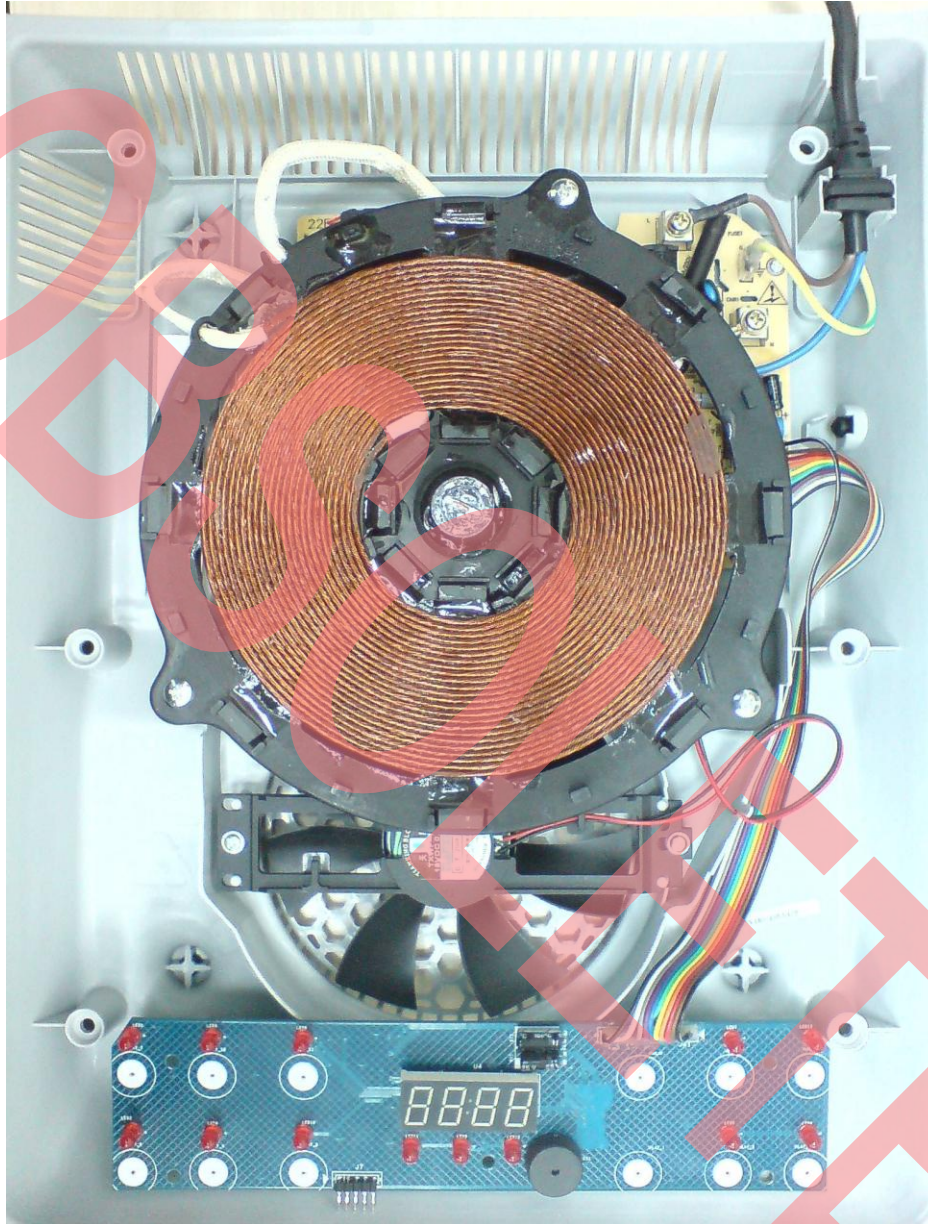
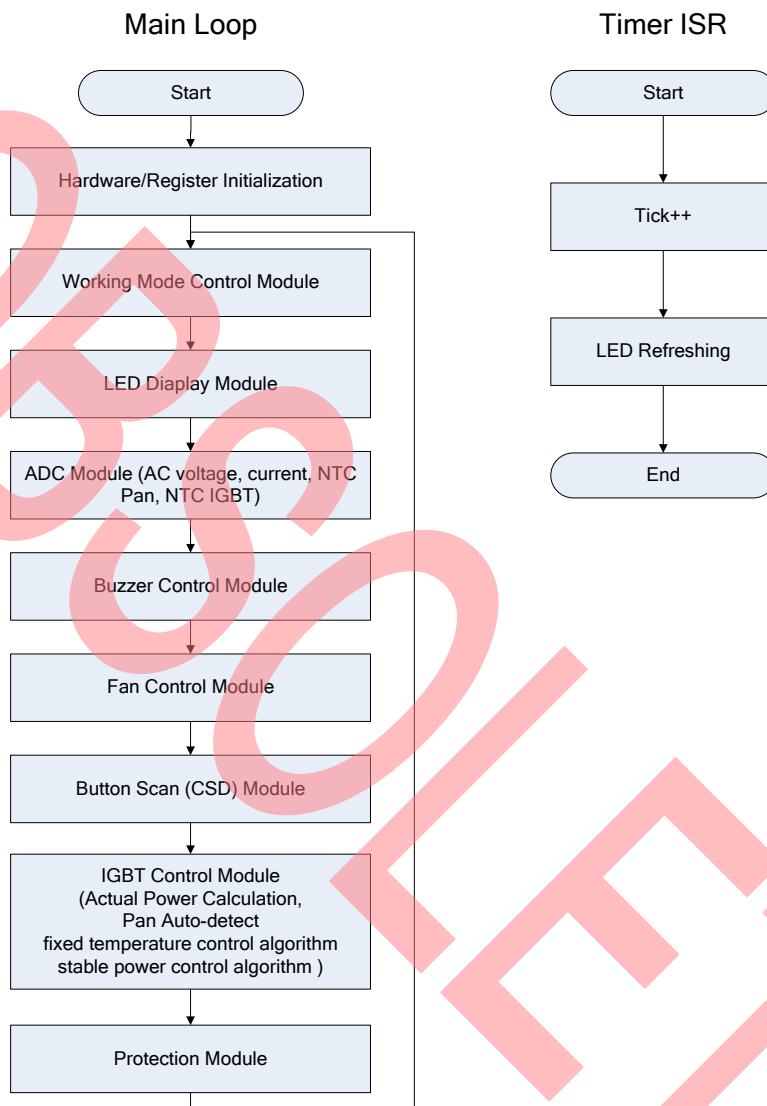


Figure 19. Induction Cooker FW Architecture Flow Chart



Document History

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Revision	ECN	Orig. of Change	Submission Date	Description of Change
**	2616863	JHU/AESA	01/07/2009	New application note.
*A	3197603	SSHH	03/16/2011	Changed the default compiler to Image craft from Hi-tech in the PSoC Designer setting.
*B	3604206	BLJI	04/30/2012	Added details about Quasi-resonant converter. Updated project to PSoC Designer 5.2 SP1. Updated template.
*C	4757034	VAIR	05/06/2015	Obsoleting this AN.

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