UM1561
User manual

STEVAL-ISV003V1: firmware user manual

Introduction

This document describes how the firmware to manage the 250 W micro-inverter demo STEVAL-ISV003V1 has been developed. Starting from the block diagram, it shows in detail the single function and provides a user guide for further code development.

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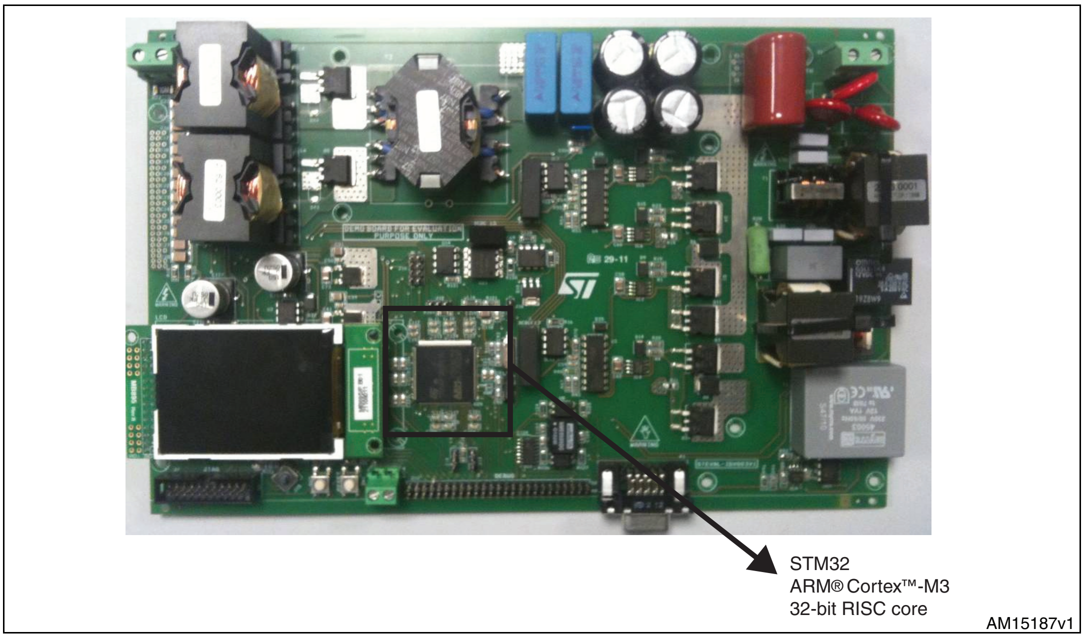
1 System overview

This demonstration board consists of an isolated interleaved boost DC-DC converter and a mixed frequency full bridge inverter used to deliver sinusoidal current at 50 Hz or 60 Hz to the grid. The board is provided with a digital control section, capable of controlling the grid-connected operation as well as an MPPT (maximum power point tracking) algorithm. The firmware has been implemented on a 32-bit STM32F1xx microcontroller, high-performance ARM® Cortex™-M3 32-bit RISC core operating at a 72 MHz frequency, high-speed embedded memories (512 Kbytes for Flash memory and 64 Kbytes of SRAM), and an extensive range of enhanced I/Os and peripherals connected to two APB buses. The device offers three 12-bit ADCs, four general-purpose 16-bit timers plus two advanced PWM timers, as well as standard and advanced communication interfaces: two I2Cs, three SPIs, two I2Ss, one SDIO, five USARTs, a USB and a CAN.

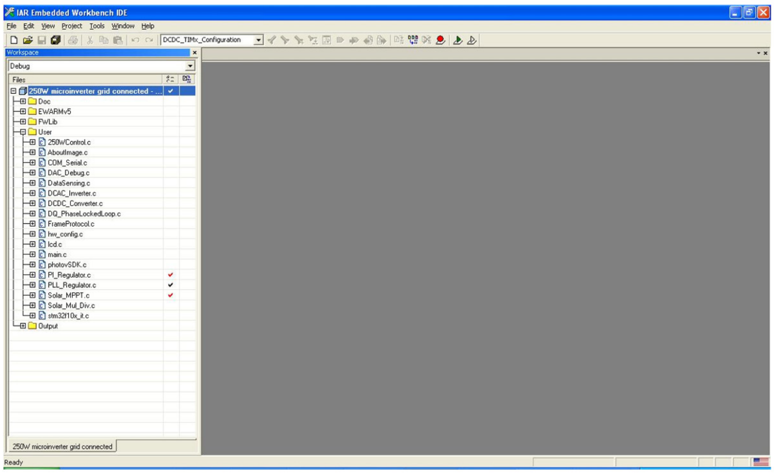
Figure 1. 250 W microinverter - digital section based on STM32F1xx microcontroller



2 Firmware workspace with IAR embedded workbench IDE

Opening IAR workbench editor, the workspace “250 W microinverter grid connected” appears as shown in *Figure 2*:

Figure 2. IAR embedded workbench IDE workspace



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It is internally structured in several folders, in particular:

- Doc: includes fw version file;
- EWARMv5: includes cortexm3_macro.s (instruction wrappers for special Cortex-M3 instructions) and stm32f10x_vector.c (STM32F10x vector table for EWARM5);
- FWLib: includes the firmware library with the .c file for each STM32F1xx internal peripheral: for example, the stm32f10x_adc.c file provides all the ADC firmware functions, stm32f10x_tim.c provides the TIM functions, and the same for other peripherals;
- User: includes all user-files developed;
- Output: contains the “.map” and “.out” file.

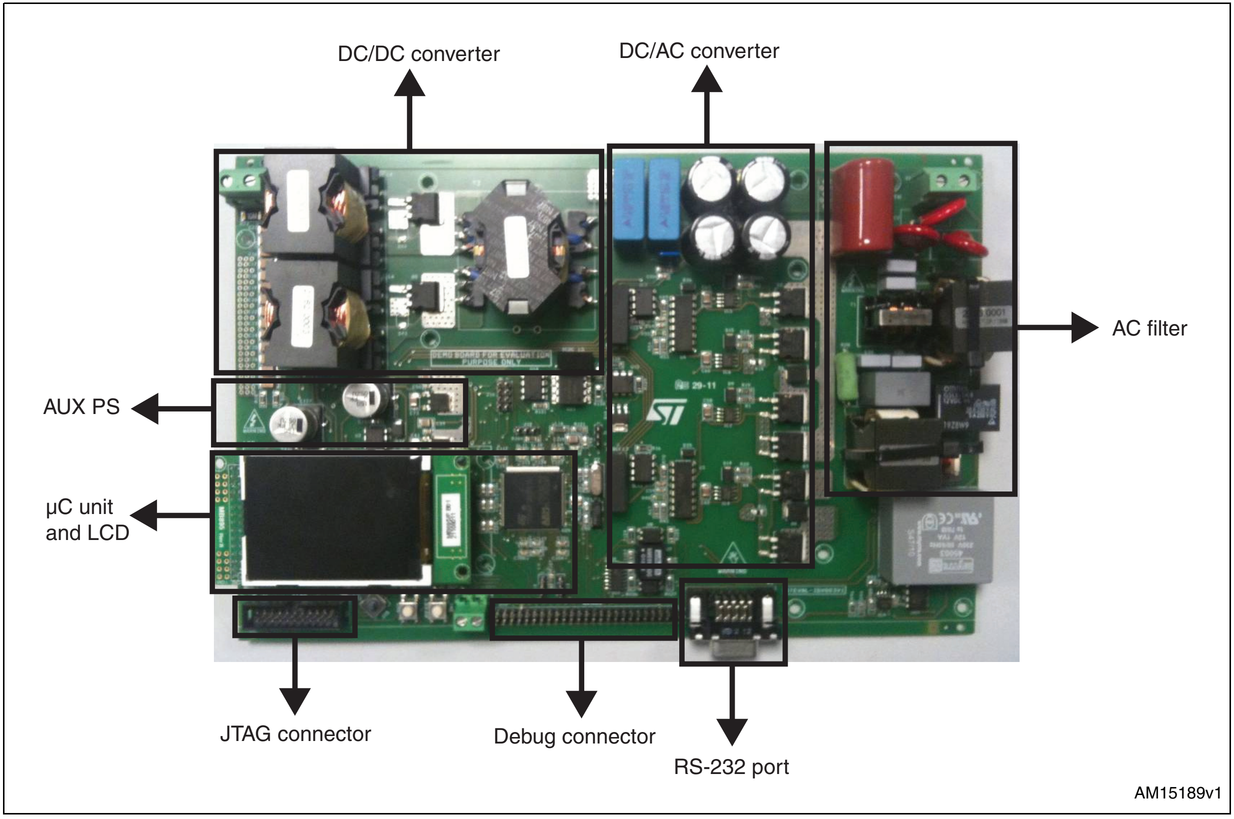
The user folder contains all .c files that contribute to the power and communication management.

- 250WControl.c: the core of the firmware; it contains a lot of functions for the closed and open loop control
- DAC_Debug.c: configures the external DAC used for debug only
- DataSensing.c: configures the data sensing section for closed loop control
- DCAC_Inverter.c: contains all functions in regard to the DCAC section
- DCDC_Inverter.c: contains all functions in regard to the DCDC section
- DQ_PhaseLockedLoop.c: contains the DQ-PLL implementation for a single-phase and the anti-islanding protection routine
- hw_config.c: configures the RCC, NVIC, GPIOs, Systick, DAC and display peripherals
- lcd.c: the library for the color display
- main.c: includes the main loop function and the system parameters management with joystick
- PI_Regulator.c: includes several PI regulators for the closed loop control
- PLL_Regulator.c: includes two PI regulators for the closed loop control, the PID_Bus_Voltage and PLL_PID regulator
- Solar MPPT: includes the maximum power point tracking algorithm for the DC-DC control
- Solar_Mul_Div.c: includes the calculations used for the closed loop control
- stm32f10x_it.c: includes main interrupt service routines.

3 STM32F1xx microcontroller - several peripherals used to manage the STEVAL-ISV003V1 demonstration board

The STEVAL-ISV003V1 is a 250 W dual stage converter digitally controlled by a 32-bit STM32F1xx microcontroller to allow operation in grid connection while performing an MPPT algorithm on the PV panel side. Several hardware peripherals, embedded in the microcontroller, have been used to control the system and to allow communication with an external unit. In particular, the power board is made up of two sections, a DC-DC converter and a DC-AC converter. *Figure 3* shows an overview of the main blocks used to design the system.

Figure 3. Description of the main hardware parts in STEVAL-ISV003V1



4 STM32F1xx - internal peripherals for DC-DC section

The DC-DC converter is managed by two PWM timers, configured in master-slave in such a way as to have two phase-shifted signals. In particular, the general timer TIM2 is configured as master with "Center Aligned" mode counting. The overflow of the digital counter at the up-counting synchronizes another general timer, TIM3, to work in slave mode. Hardware synchronization allows no delay time between the timers and two signals are generated with 180 deg. phase shift.

DCDC_Converter.c:

```
#define TIM_PERIOD        LocalDevice.Init.Counter
#define TIM2_PERIOD       (TIM_PERIOD >> 1) // DIVIDED BY 2 CENTER ALIGNED
MODE
#define TIM2_INIT_PULSE   (TIM2_PERIOD >> 1)// DIVIDED BY 2 50% TIM2 PERIOD
#define TIM3_PERIOD        (TIM_PERIOD >> 1) // DIVIDED BY 2 CENTER ALIGNED
MODE
#define TIM3_INIT_PULSE    (TIM3_PERIOD >> 1) // DIVIDED BY 2 50% TIM2 PERIOD
```

Set the counting period of the PWM timers (TIM2_PERIOD and TIM3_PERIOD), and set the duty cycle value at 50% (TIM2_INIT_PULSE, TIM3_INIT_PULSE). In DCDC_Converter.h the DCDC_COUNTER is the TIM_PERIOD reference value.

The .c file defines all functions useful in managing the DC-DC section, in particular:

- DCDC_Init(PDCDC_TypeDef_t pDCDCInit);
- DCDC_SendCommand(DCDC_Commands_t cmd);
- DCDC_GetStatus();
- DCDC_GetConfiguration(PDCDC_TypeDef_t pDCDCInit);
- DCDC_GetDutyCycle();
- DCDC_GetFrequency();
- DCDC_RefreshDisplay(DCDC_Error_t err, u32 steps, u32 changes).

DCDC_Init(....)

```
DCAC_Error_t DCAC_Init(PDCAC_TypeDef_t pDCACInit)
{
    DCAC_Error_t nRet;

    nRet = DCAC_ERROR_INVALID_PARAMETER;

    if (pDCACInit)
    {
        nRet = DCAC_ERROR_ON_INIT;
        if (LocalDevice.State != DCAC_Running)
        {
            LocalDevice.Init.Counter  = pDCACInit->Counter;
            LocalDevice.Init.DeadTime = pDCACInit->DeadTime;
            LocalDevice.State = DCAC_Stopped;
```

```
            /*Init peripherals */
            DCAC_GPIO_Configuration();
            DCAC_TIMx_Configuration();

            DCAC_SetDeadTime(LocalDevice.Init.DeadTime);

            nRet = DCAC_ERROR_NONE;
        }
    }

    return nRet;
}
```

where:
- `DCAC_GPIO_Configuration();` is (Configuration of the GPIO pin for PWM timers)
- `DCAC_TIMx_Configuration();` is (Configuration of PWM timers, TIM2 and TIM3, for master-slave mode).

DCDC_SendCommand(....)

```
DCDC_Error_t DCDC_SendCommand(DCDC_Commands_t cmd)
{
    DCDC_Error_t nRet;

    nRet = DCDC_ERROR_INVALID_COMMAND;

    if (cmd == DCDC_ConverterStart)
    {
       nRet = DCDC_ERROR_ON_SEND_COMMAND;
       if (DCDC_GetStatus() != DCDC_Running)
       {
           LocalDevice.State = DCDC_Running;
           // TIMx enable counter
            TIM_Cmd(TIM2, ENABLE);
            nRet = DCDC_ERROR_NONE;
       }
    }
    else
    if (cmd == DCDC_ConverterStop)
    {
       nRet = DCDC_ERROR_ON_SEND_COMMAND;
       if (DCDC_GetStatus() != DCDC_Stopped)
       {

         LocalDevice.State = DCDC_Stopped;
```

```
        // TIMx disable counter
           TIM_Cmd(TIM2, DISABLE);
           TIM_Cmd(TIM3, DISABLE);
           DCDC_TIMx_Configuration();
           nRet = DCDC_ERROR_NONE;
        }
     }

   return nRet;
}
```

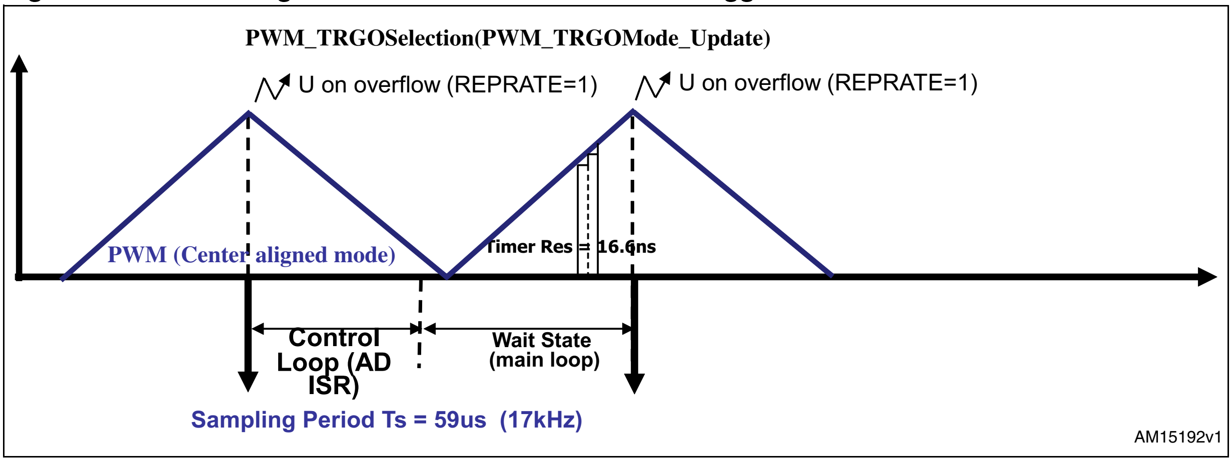
where:

- `TIM_Cmd(TIM2, ENABLE);` is (Enables PWM timer, TIM2, and the synchronization with TIM3)
- `TIM_Cmd(TIM2, DISABLE);` is (Stops the PWM timers, TIM2 and TIM3).

5 STM32F1xx - internal peripherals for DC-AC section

The DC-AC converter is managed by one PWM timer and a GPIO pin, synchronized in order to control two legs of the inverter at different switching frequencies. The advanced PWM timer, TIM8, is used to control the high frequency leg, and the GPIO pin for the low frequency leg. Only one output of the TIM8 is used and the same is true for the GPIO peripheral. The advanced timer is configured in center alignment mode in order to trigger the ADC at the up-counting of the counter. *Figure 4* shows the PWM mode and the trigger events for ADC.

Figure 4. Center alignment mode for TIM8 timer and trigger event for ADC



DataSensing.c

```
void DS_TIMx_Configuration(void)
{
//  TIM8 Configuration: PWM1 Mode

    TIM_TimeBaseStructure.TIM_Period = ((DataSensing.Init.Counter) >> 1);
    TIM_TimeBaseStructure.TIM_Prescaler = 0;
    TIM_TimeBaseStructure.TIM_ClockDivision = 0;
    TIM_TimeBaseStructure.TIM_CounterMode = TIM_CounterMode_CenterAligned1;
    TIM_TimeBaseStructure.TIM_RepetitionCounter = 1;
    TIM_TimeBaseInit(TIM8, &TIM_TimeBaseStructure);

    TIM_SelectOutputTrigger(TIM8, TIM_TRGOSource_Update);

}
```

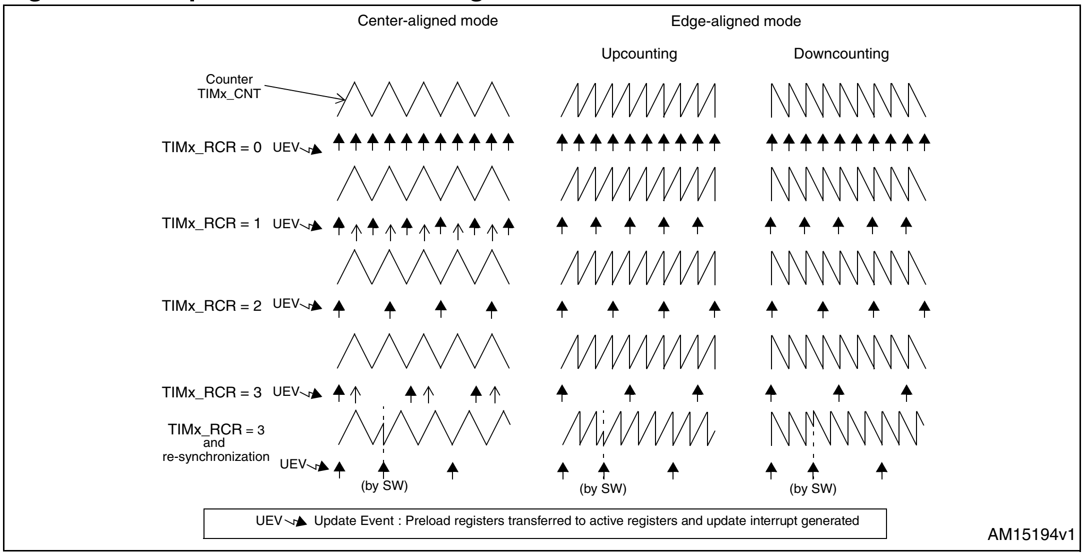
where

- `TIM_SelectOutputTrigger(TIM8, TIM_TRGOSource_Update);` is (Set the TIM8 output for ADC triggering).

The DS_TIMx_Configuration includes the configuration code for the advanced timer TIM8. The counter value (DataSensing.Init.Counter) is defined inside the DCDC_Converter.h file.

The repetition counter is set to 1 in order to have an update_event at the center of the counting, as shown in *Figure 4*.

Figure 5. Repetition counter settings for advanced timer



DCAC_Inverter.c:

The .c file defines all functions useful in managing the DC-AC section, in particular:

- DCAC_Init(PDCAC_TypeDef_t pDCACInit);
- DCAC_SendCommand(DCAC_Commands_t cmd);
- DCAC_SetPulse(u32 PulseCurrent, u32 PulseVoltage);
- DCAC_GetStatus();
- DCAC_GetConfiguration(PDCAC_TypeDef_t pDCACInit);
- DCAC_RefreshDisplay(DCAC_Error_t err, u32 steps, u32 PulseCurrent, u32 changes).

DCAC_Init(….):

```
DCAC_Error_t DCAC_Init(PDCAC_TypeDef_t pDCACInit)
{
    DCAC_Error_t nRet;

    nRet = DCAC_ERROR_INVALID_PARAMETER;

    if (pDCACInit)
    {
        nRet = DCAC_ERROR_ON_INIT;
        if (LocalDevice.State != DCAC_Running)
        {
            LocalDevice.Init.Counter  = pDCACInit->Counter;
            LocalDevice.Init.DeadTime = pDCACInit->DeadTime;
            LocalDevice.State = DCAC_Stopped;
```

```
                /*Init peripherals */
                DCAC_GPIO_Configuration();
                DCAC_TIMx_Configuration();

                DCAC_SetDeadTime(LocalDevice.Init.DeadTime);

                nRet = DCAC_ERROR_NONE;
            }
        }

        return nRet;
}
```

where:

- DCAC_GPIO_Configuration(); is (Configuration of the GPIO pin for TIM8 timer and for GPIO function)
- DCAC_TIMx_Configuration(); is (Configuration of PWM timer).

This function includes the init code for the advanced timer TIM8 and GPIO.

DCAC_SendCommand(…):

This function includes the start/stop command for the output of the advanced timer TIM8 (inverter modulation).

```
DCAC_Error_t DCAC_SendCommand(DCAC_Commands_t cmd)
{
    DCAC_Error_t nRet;

    nRet = DCAC_ERROR_INVALID_COMMAND;

    if (cmd == DCAC_Start)
    {
       nRet = DCAC_ERROR_ON_SEND_COMMAND;
       if (DCAC_GetStatus() != DCAC_Running)
       {
           LocalDevice.State = DCAC_Running;

          // TIMx enable counter
          TIM_CtrlPWMOutputs(TIM8, ENABLE);

          nRet = DCAC_ERROR_NONE;
       }
    }
    else
    if (cmd == DCAC_Stop)
    {
       nRet = DCAC_ERROR_ON_SEND_COMMAND;
```

```
        if (DCAC_GetStatus() != DCAC_Stopped)
        {
            LocalDevice.State = DCAC_Stopped;

           TIM_CtrlPWMOutputs(TIM8, DISABLE);

          // TIMx disable counter
           nRet = DCAC_ERROR_NONE;
        }
     }
   return nRet;
}
```

where:

- `TIM_CtrlPWMOutputs(TIM8, ENABLE);` is (Enables TIM8 timer for DCAC section and starts DataSensing acquisitions)
- `TIM_CtrlPWMOutputs(TIM8, DISABLE);` is (Stops TIM8 timer and stops DataSensing acquisitions).

DCAC_SetPulse(…):

This function sets the PWM pulse value produced by the calculations of the closed loop control. It is called by the microcontroller each control cycle after board startup.

```
DCAC_Error_t DCAC_SetPulse(u32 PulseChannel1, u32 PulseChannel2)
{
      DCAC_Error_t nRet;
      TIM_SetCompare2(TIM8, PulseChannel1);
      nRet = DCAC_ERROR_NONE;
    return nRet;
}
```

where:

- `TIM_SetCompare2(TIM8, PulseChannel1);` is (Set the pulse value of the TIM8 in the capture compare register).

6 Data sensing section for the closed loop control

The firmware implemented for the closed loop control needs a good sensing procedure in order to regulate the bus voltage to inject sinusoidal current to the grid and also for the input control of the DC-DC converter that performs an MPPT control. The accuracy of the control block is also very important in order to achieve system efficiency.

DataSensing.c:

The .c file defines all functions useful in managing the data sensing section, in particular:

- DS_Init(PDS_TypeDef_t pDSInit);
- DS_SendCommand(DS_Commands_t cmd);
- DS_GetStatus();
- DS_GetData();
- DS_GetConfiguration(PDS_TypeDef_t pDSInit);
- DS_RefreshDisplay(DS_Error_t err);
- DS_SetAcquistionEvent(PFN_ON_ACQUISTION pfFn).

DS_Init(..):

This function includes the init code for the ADC1 e ADC2 configuration:

```
DS_Error_t DS_Init(PDS_TypeDef_t pDSInit)
{
    DS_Error_t nRet;

    nRet = DS_ERROR_INVALID_PARAMETER;

    if (pDSInit)
    {
        nRet = DS_ERROR_ON_INIT;
        if (DataSensing.State != DS_Running)
        {
            DataSensing.Init.Counter       = pDSInit->Counter;
            DataSensing.Init.DataRegister  = pDSInit->DataRegister;
            DataSensing.Init.RegisterSize  = pDSInit->RegisterSize;
            DataSensing.Init.OnAcquisition = pDSInit->OnAcquisition;
            DataSensing.State = DS_Stopped;

            /*Init peripherals */
            DS_GPIO_Configuration();
            DS_TIMx_Configuration();
            DS_DMA_Configuration();
            DS_ADCx_Configuration();

            nRet = DS_ERROR_NONE;
        }
```

```
    }

    return nRet;
}
```

where:

- `DS_GPIO_Configuration();` is (Configures the GPIO pins)
- `DS_TIMx_Configuration();` is (Configures the TIM8 timer)
- `DS_DMA_Configuration();` is (Configures the DMA)
- `DS_DMA_Configuration();` is (Configures the ADC).

DS_GPIO_Configuration(..):

The following GPIO pins are configured as “Analog Input” in order to connect the external sensing section with the internal ADC.

```
/**************************************************************************
* Function Name  : GPIO_Configuration
* Description    : Configures the different GPIO ports for data sensing.
* Input          : None
* Output         : None
* Return         : None
**************************************************************************/
void DS_GPIO_Configuration(void)
{
    /* Configure PC.0 PC.1 (ADC Channel10, 11) as analog input -----------*/
    GPIO_InitStructure.GPIO_Pin  =
GPIO_Pin_0|GPIO_Pin_1|GPIO_Pin_2|GPIO_Pin_3|GPIO_Pin_4|GPIO_Pin_5;
    GPIO_InitStructure.GPIO_Mode = GPIO_Mode_AIN;
    GPIO_Init(GPIOC, &GPIO_InitStructure);

    /*For Debug pourpouse*/
    /* Configure Test Pin:PC9-----------------------------------*/
    GPIO_InitStructure.GPIO_Pin   = GPIO_Pin_9;
    GPIO_InitStructure.GPIO_Mode  = GPIO_Mode_Out_PP;
    GPIO_InitStructure.GPIO_Speed = GPIO_Speed_50MHz;
    GPIO_Init(GPIOC, &GPIO_InitStructure);
}
```

DS_TIMx_Configuration(..):

The DS_TIMx_Configuration includes the configuration code for the advanced timer TIM8 useful also for ADC triggering.

```
void DS_TIMx_Configuration(void)
{
//  TIM8 Configuration: PWM1 Mode

    TIM_TimeBaseStructure.TIM_Period = ((DataSensing.Init.Counter) >> 1);
    TIM_TimeBaseStructure.TIM_Prescaler = 0;
```

```
    TIM_TimeBaseStructure.TIM_ClockDivision = 0;
    TIM_TimeBaseStructure.TIM_CounterMode = TIM_CounterMode_CenterAligned1;
    TIM_TimeBaseStructure.TIM_RepetitionCounter = 1;
    TIM_TimeBaseInit(TIM8, &TIM_TimeBaseStructure);

    TIM_SelectOutputTrigger(TIM8, TIM_TRGOSource_Update);

}
```

where:

- `TIM_SelectOutputTrigger(TIM8, TIM_TRGOSource_Update);` is (Configures the TIM8 as trigger for ADC1 and ADC2).

DS_DMA_Configuration(..):

The direct memory access (DMA1) peripheral is configured to store the information acquired by the ADC in a buffer called the data register. It is a vector that includes all the I/O information, for example AC line voltage, AC line current, DC bus voltage, DC panel current, and DC panel voltage.

```
/**************************************************************************
* Function Name  : DS_DMA_Configuration
* Description    : Analog to digital converter configuration
* Input          : NONE
* Return         : None
**************************************************************************/
void DS_DMA_Configuration(void)
{
  /* DMA1 channel1 configuration ----------------------------------------*/
  DMA_DeInit(DMA1_Channel1);
  DMA_InitStructure.DMA_PeripheralBaseAddr = ADC1_DR_Address;
  DMA_InitStructure.DMA_MemoryBaseAddr =
(vu32)DataSensing.Init.DataRegister;
  DMA_InitStructure.DMA_DIR = DMA_DIR_PeripheralSRC;
  DMA_InitStructure.DMA_BufferSize = DataSensing.Init.RegisterSize;
  DMA_InitStructure.DMA_PeripheralInc = DMA_PeripheralInc_Disable;
  DMA_InitStructure.DMA_MemoryInc = DMA_MemoryInc_Enable;
  DMA_InitStructure.DMA_PeripheralDataSize = DMA_PeripheralDataSize_Word;
  DMA_InitStructure.DMA_MemoryDataSize = DMA_MemoryDataSize_Word;
  DMA_InitStructure.DMA_Mode = DMA_Mode_Circular;
  DMA_InitStructure.DMA_Priority = DMA_Priority_High;
  DMA_InitStructure.DMA_M2M = DMA_M2M_Disable;
  DMA_Init(DMA1_Channel1, &DMA_InitStructure);

  /* Enable DMA1 channel1 */
  DMA_Cmd(DMA1_Channel1, ENABLE);

  /* Clear channel1 transfer complete flag */
```

```
  DMA_ClearFlag(DMA1_FLAG_TC1);

}
```

where

- `(vu32)DataSensing.Init.DataRegister;` is (Data Register stores the I/O information).

DS_ADCx_Configuration(....):

The ADC is triggered by an external trigger. The update event of TIM8 generates the trigger signal to acquire the I/O information.

```
void DS_ADCx_Configuration(void)
{
  /* ADC1 configuration -------------------------------------------------*/
  ADC_InitStructure.ADC_Mode = ADC_Mode_RegSimult;
  ADC_InitStructure.ADC_ScanConvMode = ENABLE;
  ADC_InitStructure.ADC_ContinuousConvMode = DISABLE;
  ADC_InitStructure.ADC_ExternalTrigConv =
ADC_ExternalTrigConv_Ext_IT11_TIM8_TRGO;
  ADC_InitStructure.ADC_DataAlign = ADC_DataAlign_Left;
  ADC_InitStructure.ADC_NbrOfChannel = 3;
  ADC_Init(ADC1, &ADC_InitStructure);

  /* ADC1 regular channel10 configuration */
  ADC_RegularChannelConfig(ADC1, ADC_Channel_10, 1,
ADC_SampleTime_1Cycles5); //AC Line current
  /* ADC1 regular channel12 configuration */
  ADC_RegularChannelConfig(ADC1, ADC_Channel_12, 2,
ADC_SampleTime_1Cycles5); //DC Panel current
  /* ADC1 regular channel12 configuration */
  ADC_RegularChannelConfig(ADC1, ADC_Channel_14, 3,
ADC_SampleTime_1Cycles5); //BUS Voltage
  /*External trigger enabled*/
  ADC_ExternalTrigConvCmd(ADC1, ENABLE);

  //AFIO_REMAP for Trigger on Tim8 TRGO
  GPIO_PinRemapConfig(GPIO_Remap_ADC1_ETRGREG, ENABLE);

  /* Enable ADC1 DMA */
  ADC_DMACmd(ADC1, ENABLE);

  /* ADC2 configuration -------------------------------------------------*/
  ADC_InitStructure.ADC_Mode = ADC_Mode_RegSimult;
  ADC_InitStructure.ADC_ScanConvMode = ENABLE;
  ADC_InitStructure.ADC_ContinuousConvMode = DISABLE;
  ADC_InitStructure.ADC_ExternalTrigConv = ADC_ExternalTrigConv_None;
  ADC_InitStructure.ADC_DataAlign = ADC_DataAlign_Left;
```

```
  ADC_InitStructure.ADC_NbrOfChannel = 3;
  ADC_Init(ADC2, &ADC_InitStructure);

  /* ADC2 regular channel11 configuration */
  ADC_RegularChannelConfig(ADC2, ADC_Channel_11, 1,
ADC_SampleTime_1Cycles5);
  /* ADC2 regular channel13 configuration */
  ADC_RegularChannelConfig(ADC2, ADC_Channel_13, 2,
ADC_SampleTime_1Cycles5); //PC3 PANEL VOLTAGE
  /* ADC2 regular channel15 configuration not used */
  ADC_RegularChannelConfig(ADC2, ADC_Channel_15, 3,
ADC_SampleTime_1Cycles5);

  /*External trigger enabled*/
  ADC_ExternalTrigConvCmd(ADC2, ENABLE);

  ADC_ITConfig(ADC1, ADC_IT_EOC , ENABLE);
  DS_ADC_EnableAndCalibrate(ADC1);
  DS_ADC_EnableAndCalibrate(ADC2);

}
```

The ADC1 converts the following information at different channels:

- ADC_Channel_10 -> AC line current
- ADC_Channel_12 -> DC panel current
- ADC_Channel_14 -> DC bus voltage.

```
  /* ADC2 configuration -------------------------------------------------*/
  ADC_InitStructure.ADC_Mode = ADC_Mode_RegSimult;
  ADC_InitStructure.ADC_ScanConvMode = ENABLE;
  ADC_InitStructure.ADC_ContinuousConvMode = DISABLE;
  ADC_InitStructure.ADC_ExternalTrigConv = ADC_ExternalTrigConv_None;
  ADC_InitStructure.ADC_DataAlign = ADC_DataAlign_Left;
  ADC_InitStructure.ADC_NbrOfChannel = 3;
  ADC_Init(ADC2, &ADC_InitStructure);

  /* ADC2 regular channel11 configuration */
  ADC_RegularChannelConfig(ADC2, ADC_Channel_11, 1,
ADC_SampleTime_1Cycles5);
  /* ADC2 regular channel13 configuration */
  ADC_RegularChannelConfig(ADC2, ADC_Channel_13, 2,
ADC_SampleTime_1Cycles5);
  /* ADC2 regular channel15 configuration not used */
  ADC_RegularChannelConfig(ADC2, ADC_Channel_15, 3,
ADC_SampleTime_1Cycles5);

  /*External trigger enabled*/
  ADC_ExternalTrigConvCmd(ADC2, ENABLE);
```

```
ADC_ITConfig(ADC1, ADC_IT_EOC , ENABLE);
DS_ADC_EnableAndCalibrate(ADC1);
DS_ADC_EnableAndCalibrate(ADC2);
```

The ADC2 converts the following information at different channels:

- ADC_Channel_11 -> AC line voltage
- ADC_Channel_13 -> DC panel voltage.

7 STM32F1xx MCU peripherals configuration

hw_config.c:

The .c file defines all functions useful to init the internal and external peripherals, in particular:

- RCC_Config(): configures main system clocks & power;
- NVIC_Configuration(): configures NVIC and vector table base location;
- GPIO_Configuration(): configures the different GPIO ports;
- SysTick_Config(): configure a SysTick Base time to 1 ms;
- InitControl(..): initializes the parameters for the control algorithm (open/closed loop);
- DAC_Init(): configures DAC peripheral used only for debug;
- STM3210E_LCD_Init(): initializes the LCD.

```
void SetSystem(void)
{

    /* RCC configuration */
    RCC_Config();
    /*Interrupt vector*/
    NVIC_Configuration();

    /*GPIO Conf....*/
    GPIO_Configuration();

    /* SysTick for delay function*/
    SysTick_Config();

    /*Init 250W Control algorithm*/
    InitControl(ClosedLoop);

    //Init DAC Control
    DAC_Init(DAC_COUNTER, DAC_ADDRESS);

    /*LCD int */
    STM3210E_LCD_Init();

    /* Clear the LCD */
    LCD_Clear(White);

    /*Photovoltaic data transfer Init*/
    PHOTOVSDK_Init();

}
```

where:

- RCC_Config(); is (Configures main system clocks and power)
- NVIC_Configuration(); is (Configures NVIC and Vector Table base location)
- GPIO_Configuration(); is (Configures the different GPIO ports)
- SysTick_Config(); is (Configures the different GPIO ports)
- InitControl(ClosedLoop); is (Initializes the parameters for the control algorithm (open/closed loop))
- DAC_Init(DAC_COUNTER, DAC_ADDRESS); is (Initializes the parameters for the control algorithm (open/closed loop))
- STM3210E_LCD_Init(); is (Initializes the LCD)
- LCD_Clear(White); is (Initializes the LCD).

8 Implementation of digital phase locked loop

DQ_PhaseLockedLoop.c:

The .c file defines the DQ PLL implementation for a single-phase inverter. It is used for the closed loop control in order to estimate the grid angle and to detect the grid voltage before injecting current.

```
#include "stm32f10x_lib.h"
#include "Solar_Mul_Div.h"
#include "250WControl.h"
#define STEPS   512  /*number of entries of the sine look up table*/
#define OFFSET  64   /* Offset for cos(Theta)=sin_cos_Table[index_sin+offset]*/
#define INDUCTANCE_VALUE  65     //1117----- 34mH in q1.15= 34*10-3*2-15/
#define SAMPLES           256

#define SAMPLING_TIME     (s16)((4096)-1)

SystStatus_t Freq_Control= FREQ_OUT_OF_RANGE;
SystStatus_t GDVoltage = GRID_VOLTAGE_OUT_OF_RANGE;
```

where:

- 512: is (Number of entries of the sine look-up table).

The following code shows the look-up table with 512 elements in hexadecimal format.

```
//*********************** 512 elements *********************************
const s16 Sin_Cos_Table[STEPS] = {
//tabella USATA x IL VECTOR
0x0000, 0xFE6E, 0xFCDC, 0xFB4A, 0xF9B9, 0xF827, 0xF696, 0xF505, 0xF375,
0xF1E5, 0xF055, 0xEEC7, 0xED38, 0xEBAB, 0xEA1E, 0xE893,
0xE708, 0xE57E, 0xE3F5, 0xE26D, 0xE0E7, 0xDF61, 0xDDDD, 0xDC5A, 0xDAD8,
0xD958, 0xD7DA, 0xD65D, 0xD4E1, 0xD368, 0xD1EF, 0xD079,
0xCF05, 0xCD92, 0xCC22, 0xCAB3, 0xC946, 0xC7DC, 0xC674, 0xC50E, 0xC3AA,
0xC248, 0xC0E9, 0xBF8D, 0xBE32, 0xBCDB, 0xBB86, 0xBA33,
0xB8E4, 0xB797, 0xB64C, 0xB505, 0xB3C1, 0xB27F, 0xB141, 0xB005, 0xAECD,
0xAD97, 0xAC65, 0xAB36, 0xAA0B, 0xA8E3, 0xA7BE, 0xA69C,
0xA57E, 0xA463, 0xA34C, 0xA239, 0xA129, 0xA01D, 0x9F14, 0x9E0F, 0x9D0E,
0x9C11, 0x9B18, 0x9A23, 0x9931, 0x9843, 0x975A, 0x9674,
0x9593, 0x94B6, 0x93DC, 0x9307, 0x9236, 0x916A, 0x90A1, 0x8FDD, 0x8F1E,
0x8E62, 0x8DAB, 0x8CF9, 0x8C4B, 0x8BA1, 0x8AFC, 0x8A5B,
0x89BF, 0x8927, 0x8894, 0x8806, 0x877C, 0x86F7, 0x8676, 0x85FB, 0x8583,
0x8511, 0x84A3, 0x843B, 0x83D7, 0x8377, 0x831D, 0x82C7,
0x8276, 0x822A, 0x81E3, 0x81A1, 0x8163, 0x812B, 0x80F7, 0x80C8, 0x809E,
0x8079, 0x8059, 0x803E, 0x8028, 0x8017, 0x800A, 0x8003,
0x8000, 0x8003, 0x800A, 0x8017, 0x8028, 0x803E, 0x8059, 0x8079, 0x809E,
0x80C8, 0x80F7, 0x812B, 0x8163, 0x81A1, 0x81E3, 0x822A,
0x8276, 0x82C7, 0x831D, 0x8377, 0x83D7, 0x843B, 0x84A3, 0x8511, 0x8583,
0x85FB, 0x8676, 0x86F7, 0x877C, 0x8806, 0x8894, 0x8927,
0x89BF, 0x8A5B, 0x8AFC, 0x8BA1, 0x8C4B, 0x8CF9, 0x8DAB, 0x8E62, 0x8F1E,
0x8FDD, 0x90A1, 0x916A, 0x9236, 0x9307, 0x93DC, 0x94B6,
```

```
0x9593, 0x9674, 0x975A, 0x9843, 0x9931, 0x9A23, 0x9B18, 0x9C11, 0x9D0E,
0x9E0F, 0x9F14, 0xA01D, 0xA129, 0xA239, 0xA34C, 0xA463,
0xA57E, 0xA69C, 0xA7BE, 0xA8E3, 0xAA0B, 0xAB36, 0xAC65, 0xAD97, 0xAECD,
0xB005, 0xB141, 0xB27F, 0xB3C1, 0xB505, 0xB64C, 0xB797,
0xB8E4, 0xBA33, 0xBB86, 0xBCDB, 0xBE32, 0xBF8D, 0xC0E9, 0xC248, 0xC3AA,
0xC50E, 0xC674, 0xC7DC, 0xC946, 0xCAB3, 0xCC22, 0xCD92,
0xCF05, 0xD079, 0xD1EF, 0xD368, 0xD4E1, 0xD65D, 0xD7DA, 0xD958, 0xDAD8,
0xDC5A, 0xDDDD, 0xDF61, 0xE0E7, 0xE26D, 0xE3F5, 0xE57E,
0xE708, 0xE893, 0xEA1E, 0xEBAB, 0xED38, 0xEEC7, 0xF055, 0xF1E5, 0xF375,
0xF505, 0xF696, 0xF827, 0xF9B9, 0xFB4A, 0xFCDC, 0xFE6E,
0x0000, 0x0192, 0x0324, 0x04B6, 0x0647, 0x07D9, 0x096A, 0x0AFB, 0x0C8B,
0x0E1B, 0x0FAB, 0x1139, 0x12C8, 0x1455, 0x15E2, 0x176D,
0x18F8, 0x1A82, 0x1C0B, 0x1D93, 0x1F19, 0x209F, 0x2223, 0x23A6, 0x2528,
0x26A8, 0x2826, 0x29A3, 0x2B1F, 0x2C98, 0x2E11, 0x2F87,
0x30FB, 0x326E, 0x33DE, 0x354D, 0x36BA, 0x3824, 0x398C, 0x3AF2, 0x3C56,
0x3DB8, 0x3F17, 0x4073, 0x41CE, 0x4325, 0x447A, 0x45CD,
0x471C, 0x4869, 0x49B4, 0x4AFB, 0x4C3F, 0x4D81, 0x4EBF, 0x4FFB, 0x5133,
0x5269, 0x539B, 0x54CA, 0x55F5, 0x571D, 0x5842, 0x5964,
0x5A82, 0x5B9D, 0x5CB4, 0x5DC7, 0x5ED7, 0x5FE3, 0x60EC, 0x61F1, 0x62F2,
0x63EF, 0x64E8, 0x65DD, 0x66CF, 0x67BD, 0x68A6, 0x698C,
0x6A6D, 0x6B4A, 0x6C24, 0x6CF9, 0x6DCA, 0x6E96, 0x6F5F, 0x7023, 0x70E2,
0x719E, 0x7255, 0x7307, 0x73B5, 0x745F, 0x7504, 0x75A5,
0x7641, 0x76D9, 0x776C, 0x77FA, 0x7884, 0x7909, 0x798A, 0x7A05, 0x7A7D,
0x7AEF, 0x7B5D, 0x7BC5, 0x7C29, 0x7C89, 0x7CE3, 0x7D39,
0x7D8A, 0x7DD6, 0x7E1D, 0x7E5F, 0x7E9D, 0x7ED5, 0x7F09, 0x7F38, 0x7F62,
0x7F87, 0x7FA7, 0x7FC2, 0x7FD8, 0x7FE9, 0x7FF6, 0x7FFD,
0x7FFF, 0x7FFD, 0x7FF6, 0x7FE9, 0x7FD8, 0x7FC2, 0x7FA7, 0x7F87, 0x7F62,
0x7F38, 0x7F09, 0x7ED5, 0x7E9D, 0x7E5F, 0x7E1D, 0x7DD6,
0x7D8A, 0x7D39, 0x7CE3, 0x7C89, 0x7C29, 0x7BC5, 0x7B5D, 0x7AEF, 0x7A7D,
0x7A05, 0x798A, 0x7909, 0x7884, 0x77FA, 0x776C, 0x76D9,
0x7641, 0x75A5, 0x7504, 0x745F, 0x73B5, 0x7307, 0x7255, 0x719E, 0x70E2,
0x7023, 0x6F5F, 0x6E96, 0x6DCA, 0x6CF9, 0x6C24, 0x6B4A,
0x6A6D, 0x698C, 0x68A6, 0x67BD, 0x66CF, 0x65DD, 0x64E8, 0x63EF, 0x62F2,
0x61F1, 0x60EC, 0x5FE3, 0x5ED7, 0x5DC7, 0x5CB4, 0x5B9D,
0x5A82, 0x5964, 0x5842, 0x571D, 0x55F5, 0x54CA, 0x539B, 0x5269, 0x5133,
0x4FFB, 0x4EBF, 0x4D81, 0x4C3F, 0x4AFB, 0x49B4, 0x4869,
0x471C, 0x45CD, 0x447A, 0x4325, 0x41CE, 0x4073, 0x3F17, 0x3DB8, 0x3C56,
0x3AF2, 0x398C, 0x3824, 0x36BA, 0x354D, 0x33DE, 0x326E,
0x30FB, 0x2F87, 0x2E11, 0x2C98, 0x2B1F, 0x29A3, 0x2826, 0x26A8, 0x2528,
0x23A6, 0x2223, 0x209F, 0x1F19, 0x1D93, 0x1C0B, 0x1A82,
0x18F8, 0x176D, 0x15E2, 0x1455, 0x12C8, 0x1139, 0x0FAB, 0x0E1B, 0x0C8B,
0x0AFB, 0x096A, 0x07D9, 0x0647, 0x04B6, 0x0324, 0x0192,
};
```

Calc_Theta_Grid (….):

The main function “Calc_Theta_Grid()” includes the code for the grid angle estimation and anti-islanding protection:

```
void Calc_Theta_Grid(s16 Input_Integration)
{
 static s32 Delta_Theta_tmp=0;
```

```
static s16 Delta_Theta=0;
static u16 freq_monitor_time=0;

mul_q15_q15_q31(Input_Integration,SAMPLING_TIME,&Delta_Theta_tmp);

Delta_Theta = (s16)(Delta_Theta_tmp>>16);

Theta=Theta+Delta_Theta;//

Theta_time++;

 if(zero_detect==50)
{
  VqFiltered_min=65500;
  VqFiltered_max=0;
  Theta_time=0;
  zero_detect=0;
}

VqFiltered_prec = (u16)(Grid_Volt_q_d.qV_Quadrature + 0x8000);

VqFiltered = (u16)(((s32)(((s32)VqFiltered<<8) - (s32)VqFiltered) +
(s32)(VqFiltered_prec))>>8);

 if(VqFiltered>VqFiltered_max) VqFiltered_max=VqFiltered;
 else if(VqFiltered<VqFiltered_min) VqFiltered_min=VqFiltered;

 VqFiltered_mean=(u16)((VqFiltered_max+VqFiltered_min)>>1);
```

where:

- `Theta=Theta+Delta_Theta;//` is (Grid angle estimation: Theta changes value linearly each switching period between -32768 to 32768).

The anti-islanding protection is based on grid voltage and frequency monitoring. The “Vq” DC-component, used for the first, is made up of an offset value (32768) plus a DC-value function of the AC Vrms value (for example Vac=265 Vrms -> Vq=39080 or Vac=186 V -> Vq=37150).

```
 //265V max & 186V min
  if((VqFiltered_mean>=39080 || VqFiltered_mean<=37150) &&
State_Control==GRID_INSERTION && MPPT_EN==TRUE && zero_detect>5 &&
Vacprot==TRUE)
  {
      GPIO_ResetBits(GPIOA, GPIO_Pin_1);
      State_Control = STOP_WITH_DELAY;
      Diagnostic_Control=GRID_VOLTAGE_OUT_OF_RANGE;
  }
```

where:

- `37150` is (AC voltage protection based on Vq value).

The figure code shows the procedure to control the AC line before the microinverter start-up: in this example, the AC line voltage must be comprised between 185 V and 265 V and the frequency between 47 Hz and 53 Hz. If these conditions are satisfied for a fixed time (10 sec), the state machine goes to the next step (DC-DC/DC-AC turned on).

```
//****************** ANTI-ISLANDING DETECTION ****************************
 if(((Theta+0x8000)-Theta_previous)<=-20000)
 {
  zero_detect++;

//************* DIAGNOSTIC AC - VOLTAGE AND FREQ AT STARTUP ***************
  //Freq 47 Hz - 53 Hz
  //Vac 185V - 265V
  if((State_Control==DIAGNOSTIC_AC_LINE) ||
(State_Control==DIAGNOSTIC_DC_LINE))
  {
    if((Theta_time>331 && Theta_time<375) && (VqFiltered_mean >= 37150 &&
VqFiltered_mean<=39080))
    {
      if(freq_monitor_time>=500) //10 sec
      {
        GDVoltage = GRID_VOLTAGE_INSIDE_RANGE;
        Freq_Control = FREQ_INSIDE_RANGE;
        freq_monitor_time=0;
      }
      if(Freq_Control==FREQ_OUT_OF_RANGE && GDVoltage ==
GRID_VOLTAGE_OUT_OF_RANGE)
         freq_monitor_time++;
     }
    else
     {
       freq_monitor_time=0;
       Grid_Voltage_max=0;
       Grid_Voltage_min=0;
     }
   }
```

where:

- `37150` is (AC voltage RMS monitoring)
- `375` is (AC frequency monitoring)
- `500` is (listening time).

9 Digital closed loop control and diagnostic functions implemented

250WControl.c:

This is the main file of the microinverter. It includes the firmware-code for the closed and open loop control, the input and output protection and the LCD display management. The first function, called InitControl(), contains the init data for the DC-DC and DC-AC section. In particular, the DC-DC information is contained in the InitStructure, the DC-AC are contained in the DCAC_InitStructure and the data sensing part in the DS_ InitStructure.

```
void InitControl(ControlMode_t mode)
{
    GPIO_InitTypeDef GPIO_InitStructure;
    DCDC_TypeDef_t InitStructure;
    DCAC_TypeDef_t DCAC_InitStructure;
    DS_TypeDef_t DS_InitStructure;

    /*DCDC Converter configuration */
    InitStructure.Counter = DCDC_COUNTER;
    InitStructure.DutyCycle = DCDC_DUTYCYCLE;
    InitStructure.frequency = DCDC_FREQUENCY;
    DCDC_Init(&InitStructure);

    /*DCAC Inverter init configuration*/
    DCAC_InitStructure.Counter = DCAC_COUNTER;
    DCAC_InitStructure.DeadTime = DCAC_DEADTIME;
    DCAC_Init(&DCAC_InitStructure);

    ControlMode = mode;
    /*DataSensing Init configuration*/
    DS_InitStructure.Counter = DCAC_COUNTER; //--the same counter of the
DCAC
    DS_InitStructure.DataRegister =  (vu32 *)&DataSensingIO;
    DS_InitStructure.RegisterSize = DATA_SENSING_SIZE;
    if (mode == ClosedLoop)
      DS_InitStructure.OnAcquisition = ExecControl;
    else
      DS_InitStructure.OnAcquisition = ExecControlOpenLoop;
      DS_Init(&DS_InitStructure);

    /*Calibration of data sensing ***AFTER DS_Init*** */

    CalibrationControl();

    /* Configure RELE   : PA1-----------------------------------*/
```

```
    GPIO_InitStructure.GPIO_Pin   = GPIO_Pin_1;
    GPIO_InitStructure.GPIO_Mode  = GPIO_Mode_Out_PP;
    GPIO_InitStructure.GPIO_Speed = GPIO_Speed_50MHz;
    GPIO_Init(GPIOA, &GPIO_InitStructure);

    PID_Init_Integral_Part();
    PID_Init(&Direct_Current_PID, &Quadrature_Current_PID,
&Reactive_Power_PID,&Active_Power_PID,&BUS_Voltage_PID,&DQ_PLL_PID,
&MPPT_PID);

    //Get Control Parameters address
    GetControlParametersAddress((PControlParam_t)&CtrlParam);
    //Get Data Parameters address
    GetDataParametersAddress((PPhotov_t)&Data);

}
```

where:

- `InitStructure.DutyCycle = DCDC_DUTYCYCLE;` is (DC-DC data structure)
- `DCAC_InitStructure.Counter = DCAC_COUNTER;` is (DC-AC data structure)
- `DS_InitStructure.Counter = DCAC_COUNTER;` is (Sensing data structure).

The StartControl() function defines the init configuration for all PID regulators. It contains also the start commands for the power section.

```
void StartControl()
{
    PID_Init_Integral_Part();
    PID_Init(&Direct_Current_PID, &Quadrature_Current_PID,
&Reactive_Power_PID,&Active_Power_PID,&BUS_Voltage_PID,&DQ_PLL_PID,
&MPPT_PID);
    BusOverVoltage = FALSE;
    GridOutage = FALSE;
    Fault = FAULT_NONE;
    StoppingCount = TIME_OUT_STOPPING;
    State_Control= DIAGNOSTIC_AC_LINE;

      (DCAC_Start);
    DS_SendCommand(DS_Start);

    if (ControlMode == OpenLoop)
     DCDC_SendCommand(DCDC_ConverterStart);
     DAC_Start();
}
```

where:

- `PID_Init(&Direct_Current_PID;` is (Init the PID regulator)
- `DS_SendCommand(DS_Start);` is (All power sections started).

The ExecControlInitParamOffset() calculates the offset value of the I/O variables, in particular the DC-components (DC_PanelVoltage, the DC_PanelCurrent) and the AC-components (AC_LineVoltage, AC_LineCurrent).

The offset values are calculated reading the I/O information for a fixed time (5 seconds). It is done to achieve the accuracy of the AC values. No manual calibration is needed.

```
void ExecControlInitParamOffSet()
{

   DataSensing_sum.DC_PanelVoltage += (u16)(DataSensingIO.DC_PanelVoltage);
   DataSensing_sum.DC_PanelCurrent += (u16)(DataSensingIO.DC_PanelCurrent);
   DataSensing_sum.AC_LineVoltage += (u16)(DataSensingIO.AC_LineVoltage);
   DataSensing_sum.AC_LineCurrent += (u16)(DataSensingIO.AC_LineCurrent);

     if (DataInitCount < (MAX_DATA_INIT_COUNT-1))
       DataInitCount++;
     else if(DataInitCount==(MAX_DATA_INIT_COUNT-1))
    {
      ((vu16*)&DataSensingOffSet)[0] = DataSensing_sum.AC_LineCurrent / 
(DataInitCount+1);
      ((vu16*)&DataSensingOffSet)[1] = DataSensing_sum.AC_LineVoltage / 
(DataInitCount+1);
      ((vu16*)&DataSensingOffSet)[2] = DataSensing_sum.DC_PanelCurrent / 
(DataInitCount+1);
      ((vu16*)&DataSensingOffSet)[3] = DataSensing_sum.DC_PanelVoltage / 
(DataInitCount+1);
      DataInitCount++;
    }
}
```

where:

- if `(DataInitCount < (MAX_DATA_INIT_COUNT-1))` is (Time for offset estimation (5 seconds)).

The firmware is based on state machines architecture able to indicate the real operation of the power board for each instant.

```
switch (State_Control)
    {
    case STOPPING:
        sprintf(strLineMessage, "STOPPING");
        break;
    case STOP:
        sprintf(strLineMessage, "STOP");
        break;
    case START:
        sprintf(strLineMessage, "START");
        break;
    case BUS_FAULT:
```

```
        sprintf(strLineMessage, "BUS_FAULT");
        break;
    case DIAGNOSTIC_DC_LINE:
        sprintf(strLineMessage, "DIAGNOSTIC_DC_LINE");
        break;
    case OUT_CURRENT_LIMIT:
        sprintf(strLineMessage, "OUT_CURRENT_LIMIT");
        break;
    case BUSPRECHARGE:
        sprintf(strLineMessage, "BUSPRECHARGE");
        break;
    case DIAGNOSTIC_AC_LINE:
        sprintf(strLineMessage, "DIAGNOSTIC_AC_LINE");
        break;
    case PV_VOLTAGE_DVDT:
        sprintf(strLineMessage, "PV_VOLTAGE_DVDT");
        break;
    case PV_VOLTAGE_MIN:
        sprintf(strLineMessage, "PV_VOLTAGE_MIN");
        break;
    case FREQ_OUT_OF_RANGE:
        sprintf(strLineMessage, "FREQ_OUT_OF_RANGE");
        break;
    case STOP_WITH_DELAY:
        sprintf(strLineMessage, "STOP_WITH_DELAY");
```

```
break;
```

- In particular, the following states indicate the status of the power converter:
  - STOPPING: the power board is going to stop the DC-DC and DC-AC section
  - STOP: power board is off and is ready to restart
  - START/BUSPRECHARGE: the DC-DC and DC-AC section are on. The burst mode charges the bus capacitor before the grid insertion
  - GRID INSERTION: the microinverter is grid connected and the MPPT algorithm is enabled to transfer maximum power from the PV module
- Diagnostic states:
  - DIAGNOSTIC AC LINE: it verifies the AC line voltage inside the range (Vac_rms, Freq_vac)
  - DIAGNOSTIC DC LINE: it verifies the PV module voltage inside the range
- Protection states:
  - OUT CURRENT LIMIT: the output AC current reaches the maximum value
  - PV VOLTAGE DVDT: the MCU detects low irradiance condition of the PV module
  - PV VOLTAGE MIN: the PV module goes below the minimum voltage value
  - FREQ OUT OF RANGE: the AC line frequency is out of range
  - STOP WITH DELAY: the power board is waiting to stop the modulation after the open-relay
  - BUS FAULT: bus overvoltage or undervoltage protection state; the status changes to STOPPING after modulation switch-off.

Closed loop control calculation

This is the main function for the closed loop control. It comprises the code to regulate the bus voltage and to manage the output current in grid insertion mode. In particular, for the greater part of the control, it is based on PID regulators such as the following:

- PID_Bus_Voltage(&BUS_Voltage_PID, Bus_Voltage);
- PID_Reactive_Power(&Reactive_Power_PID, Actual_QD_Power.Q_Reactive);
- PID_DirectCurrent(&Direct_Current_PID, Inverter_q_d.qI_Direct);
- PID_QuadratureCurrent(&Quadrature_Current_PID, Inverter_q_d.qI_Quadrature).

This part of the calculation, together with the reverse park transformation (with the circle limitation), generates as the output the PWM duty cycle value for the DC-AC section. This function is called at switching frequency.

```
void CalcAndSetACComponents(SystStatus_t state)
{

    Quadrature_Current_PID.Reference=
PID_Bus_Voltage(&BUS_Voltage_PID,Bus_Voltage);
    Direct_Current_PID.Reference = PID_Reactive_Power(&Reactive_Power_PID,
Actual_QD_Power.Q_Reactive);

    Output_qId_Inverter= (s16)(PID_DirectCurrent(&Direct_Current_PID,
Inverter_q_d.qI_Direct));
```

```
    Output_qIq_Inverter=
(s16)(PID_QuadratureCurrent(&Quadrature_Current_PID,
Inverter_q_d.qI_Quadrature));

    RevPark_Circle_Limitation();

    Control_Volt_AlphaBeta=
Rev_Park(Output_qIq_Inverter,Output_qId_Inverter);

    if(State_Control!=DIAGNOSTIC_DC_LINE &&
State_Control!=DIAGNOSTIC_AC_LINE && State_Control!=BUSPRECHARGE)
    {
    if(Control_Volt_AlphaBeta.qValpha <= 0)
    {
          GPIOB->BRR = GPIO_Pin_8;
          Pulse1 = (u16)(new_mul_q15_q15_q31(-
Control_Volt_AlphaBeta.qValpha, MODINDEX) >> 16);
          DCAC_SetPulse(Pulse1,Pulse1);
     }
       else if(Control_Volt_AlphaBeta.qValpha > 0)
        {
           GPIOB->BSRR = GPIO_Pin_8;
          Pulse2 = (u16)(new_mul_q15_q15_q31((s16)(0x8000 -
Control_Volt_AlphaBeta.qValpha), MODINDEX) >> 16);
          DCAC_SetPulse(Pulse2,Pulse2);
       }
    }
}
```

where:

```
    if(Control_Volt_AlphaBeta.qValpha <= 0)
    {
          GPIOB->BRR = GPIO_Pin_8;
          Pulse1 = (u16)(new_mul_q15_q15_q31(-
Control_Volt_AlphaBeta.qValpha, MODINDEX) >> 16);
          DCAC_SetPulse(Pulse1,Pulse1);
     }
```

is (10 msec window).

- `GPIOB->BRR = GPIO_Pin_8;` is (GPIO pin for low frequency modulation)
- `GPIOB->BSRR = GPIO_Pin_8;` is (GPIO pin for low frequency modulation)
- `Pulse1 = (u16)(new_mul_q15_q15_q31(-Control_Volt_AlphaBeta.qValpha, MODINDEX) >> 16);` is (PWM calculation for high frequency modulation)
- `Pulse2 = (u16)(new_mul_q15_q15_q31((s16)(0x8000 - Control_Volt_AlphaBeta.qValpha), MODINDEX) >> 16);` is (PWM calculation for high frequency modulation).

10 MPPT - maximum power point algorithm

The overall control architecture for the input side of the power converter requires three feedback signals for correct operation, input panel current and input panel voltage are used for maximum power point tracking; the output bus voltage is used for monitoring the OV condition and to control the starting/stopping procedure.

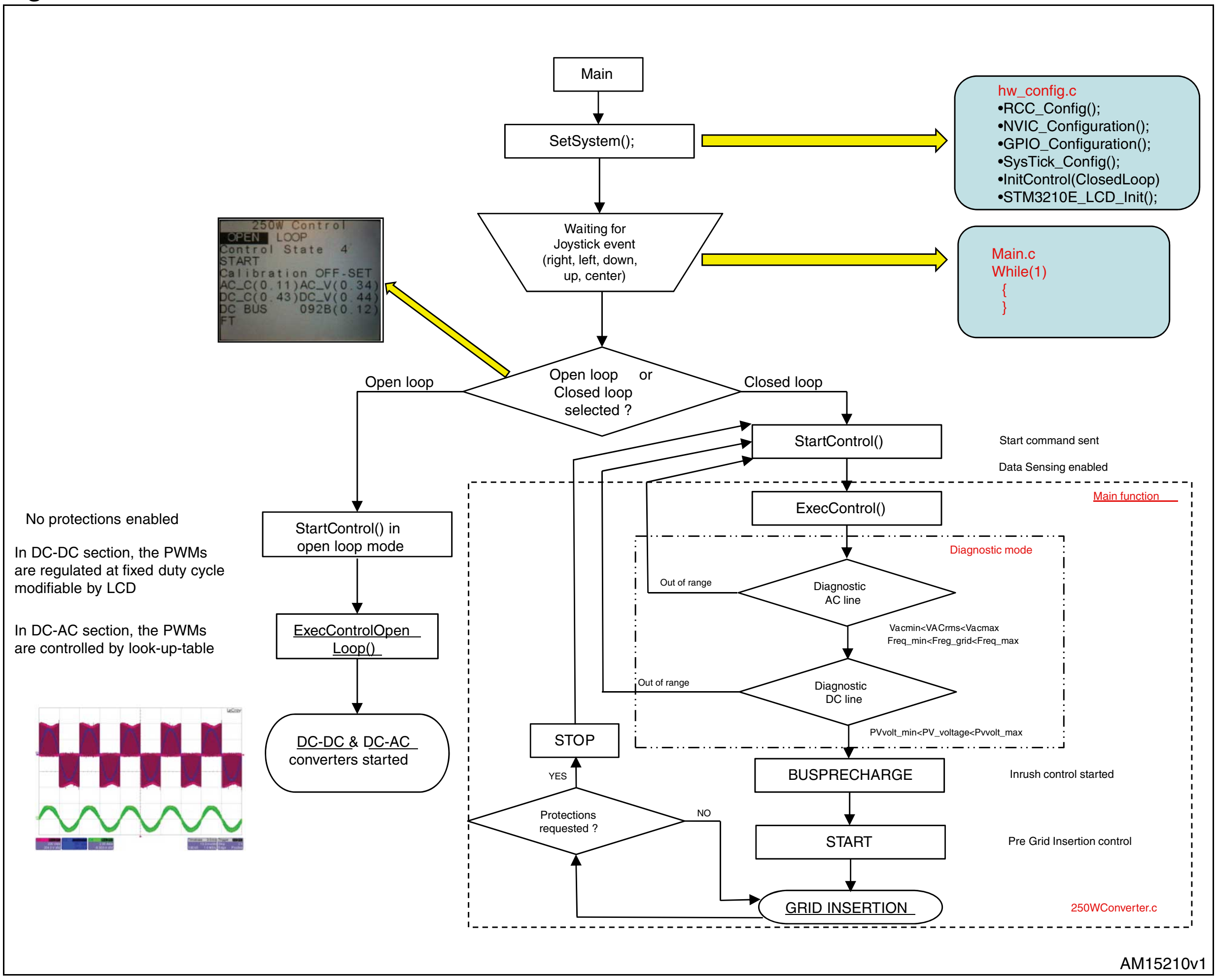
These signals are sent to the ADC inputs of the microcontroller, according to the pin assignment, and in function of these values, two timers generate PWM output to drive the DC-DC Power MOSFETs or disable the driving signals to turn off the module, isolating the solar panel from the output bus. The duty cycle value is regulated by a maximum power point tracking algorithm embedded in the STM32F1xx microcontroller.

This algorithm is developed inside the MPPT_func(). Starting from I/O information (PV_voltage and PV_current), the DC power is calculated and in function of the PV_voltage, it regulates the duty cycle value of the two PWM timers.

```
void MPPT_func()
{
  CCR_Val = (u16) DCDC_GetDutyCycle();
  Vpanel=PV_Voltage;
  Ipanel=PV_Current;
  if(Ipanel==0) Ipanel=1;
  Pow = (u32)((u32)Vpanel * (u32)Ipanel);
  if(flag_mppt==1) { Step_modify(); }

    if((Pow >= Powprev) && (Vpanel <= Vpanel_prev))
     {
   if((CCR_Val - CCR_Val_step)<=235)
         {
      CCR_Val=235;
           DCDC_SetDutyCycle((u16)CCR_Val);
         }
   else
         {
           CCR_Val=CCR_Val - CCR_Val_step;
           DCDC_SetDutyCycle((u16)CCR_Val);
     }
     }
  if((Pow > Powprev) && (Vpanel > Vpanel_prev))
   {
   if((CCR_Val + CCR_Val_step)>=512)
     {
        CCR_Val=512;
             DCDC_SetDutyCycle((u16)CCR_Val);
     }
   else
          {
```

```
            CCR_Val = CCR_Val + CCR_Val_step;
          DCDC_SetDutyCycle((u16)CCR_Val);
        }
            }
      if((Pow<Powprev) && (Vpanel<Vpanel_prev))
        {

        if((CCR_Val +CCR_Val_step)>=512)
          {
           CCR_Val=512;
                 DCDC_SetDutyCycle((u16)CCR_Val);
          }
         else
                {
                 CCR_Val = CCR_Val + CCR_Val_step;
           flag_mppt=1;
                 DCDC_SetDutyCycle((u16)CCR_Val);
                }
              }

         if((Pow<=Powprev) && (Vpanel>=Vpanel_prev))
         {
           if((CCR_Val - CCR_Val_step)<=235)
             {
         CCR_Val=235;
                    DCDC_SetDutyCycle((u16)CCR_Val);
              }
           else
                 {
                   CCR_Val = CCR_Val - CCR_Val_step;
                   DCDC_SetDutyCycle((u16)CCR_Val);
                 }
               }
     Powprev = Pow;
     Vpanel_prev= Vpanel;
     Pow=0;
   }
```

Figure 6. 250W microinverter - firmware flow chart



11 Input/output protection

The power board is also controlled by the microcontroller for the input/output protection. During normal operation it is possible that the cables (input or output side) are accidentally disconnected from the panel or from the grid. In this case, overcurrent or overvoltage may appear at the power stage. To avoid damaging the electronic parts, a procedure is implemented in the 250WControl.c file, as follows:

```
if (BusFiltered > 13000)
        {
         Fault = BUS_OVERVOLTAGE;
         GPIO_ResetBits(GPIOA, GPIO_Pin_1);
         State_Control = STOP_WITH_DELAY;
         Diagnostic_Control=BUS_OVERVOLTAGE;
        }
     if (BusFiltered < 9880 && MPPT_EN==TRUE)
        {
         Fault = BUS_UNDERVOLTAGE;
         GPIO_ResetBits(GPIOA, GPIO_Pin_1);
         State_Control = STOP_WITH_DELAY;
         Diagnostic_Control=BUS_UNDERVOLTAGE;
        }
```

where:

- `Fault = BUS_OVERVOLTAGE;` is (Bus overvoltage detected)
- `Fault = BUS_UNDERVOLTAGE;` is (Bus undervoltage detected).

```
  if((qIalpha_Inverter > 19667 || qIalpha_Inverter <-19667) &&
State_Control==GRID_INSERTION && MPPT_EN==TRUE) //1.6 max output peak
current
   {
      Fault = OUT_CURRENT_LIMIT;
      GPIO_ResetBits(GPIOA, GPIO_Pin_1);
      State_Control = STOP_WITH_DELAY;
      Diagnostic_Control=OUT_CURRENT_LIMIT;
   }
```

where:

- `GPIO_ResetBits(GPIOA, GPIO_Pin_1);` is (AC line overcurrent detected)
- `State_Control = STOP_WITH_DELAY;` is (PV_module Vmin detected).

```
if(PV_Voltage<=11000 && State_Control==GRID_INSERTION) //22V min
  {
      GPIO_ResetBits(GPIOA, GPIO_Pin_1);
      State_Control = STOP_WITH_DELAY;
      Diagnostic_Control=PV_VOLTAGE_MIN;
  }
```

When a bus over/undervoltage, overcurrent or minimum input voltage appears, the closed loop control stops the MPPT function and it moves to the next state machine (STOP_WITH_DELAY). At this point, the power board is waiting for a physical opening of the relay. During the fixed time (10 msec) the PWM continues to modulate at the DC-DC stage and the DC-AC stage. At the end of this period, they all switch off. This time is in accordance with the relay specifications.

12 Revision history

Table 1. Document revision history

Date	Revision	Changes
16-Oct-2012	1	Initial release.

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