



## Introduction

The aim of this Application Note is to give an example of how to use the ST7MC microcontroller to implement the Power Factor Correction (PFC) inside a motor control application. The ST7MC microcontroller is provided with a Motor Control Peripheral which has been developed to implement motor control function for Induction motors and Permanent Magnet Synchronous motors. The motor control peripheral leaves the microcontroller resources free to perform the power factor correction.

The power factor correction technique utilized is called “transition mode”. The hardware used to realize the system is the ST7MC Starter Kit plus an additional external power board called “Add On”.

In this application note, theoretical information about the PFC control method is given, in addition to an explanation of the software routine able to manage the PFC stage and the calculation of the Add On components.

The reader can find extra information about the motor control related routines the application note AN1904.

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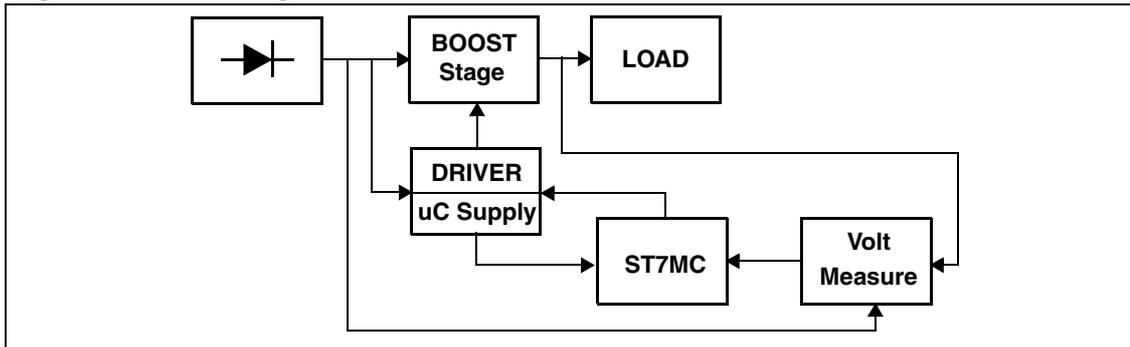
# 1 Theory about the PFC

This application note focuses on the management by a microcontroller of the boost stage to obtain a power factor corrector (PFC) working in transition mode.

Of course to do this job the microcontroller should have a timer with a special feature.

A block diagram of the application is shown in *Figure 1*.

**Figure 1. Block diagram**



## 1.1 Description

With this method, the boost inductor works on the boundary between continuous and discontinuous mode. In this operation mode there is a high peak current which means that this kind of approach could be used for power below 600W.

Here, the system works with fixed ON-time and variable frequency and functions as follows:

The main supply is rectified by the bridge and the energy is stored in the transformer during the turn-on period of the mosfet. This time interval is called  $T_{on}$  and must be calculated by the Micro according to the  $V_{out}$  value, the input voltage and the load.

To simplify the algorithm, just the output voltage is measured and the difference (error) between the desired values (400V) and the actual value is calculated. This error is multiplied by a constant to obtain the right correction value.

The measured voltage value is the average of eight ADC conversions.

The turn-off time of the mosfet is called  $T_{off}$  and is fixed by the circuit. This means the inductor discharges all its own energy to the output stage until its current goes to zero.

In this condition, the drain Voltage will go to the  $V_{in}$  voltage and an oscillation due to the MOS capacitance is added to this voltage.

In order to reduce the commutation losses, the MOS must be turned ON when the Drain voltage reaches the minimum.

To detect this condition the secondary winding of the transformer is used. In fact, in this secondary winding is a square wave with zero mean value which is made up of a negative signal during the  $T_{on}$  and a positive signal during the  $T_{off}$ . To adapt this signal to the digital world of a microcontroller a resistor to limit the current plus the internal clamping diodes have been used to obtain a square TTL waveform.

So, finally, a TTL square wave is obtained on the microcontroller pin which is used by the timer peripheral to restart the counter cycle and fix the counter period.

For the timer, it's important to note that if there isn't a load variation and/or a variation of the input voltage, it could work as a standalone circuit without any computational time required to the micro. In fact, if the zero current condition (ZCD) is missed the timer will restart at the minimum frequency through a software routine.

Of course the availability of the micro makes a lot of features possible simply by modifying some parameters and it also allows a particular software routine to be used to improve the control method.

The output of the PWM timer is connected to the TD220 driver that drives the MOS of the boost stage.

## 2 Starter kit approach

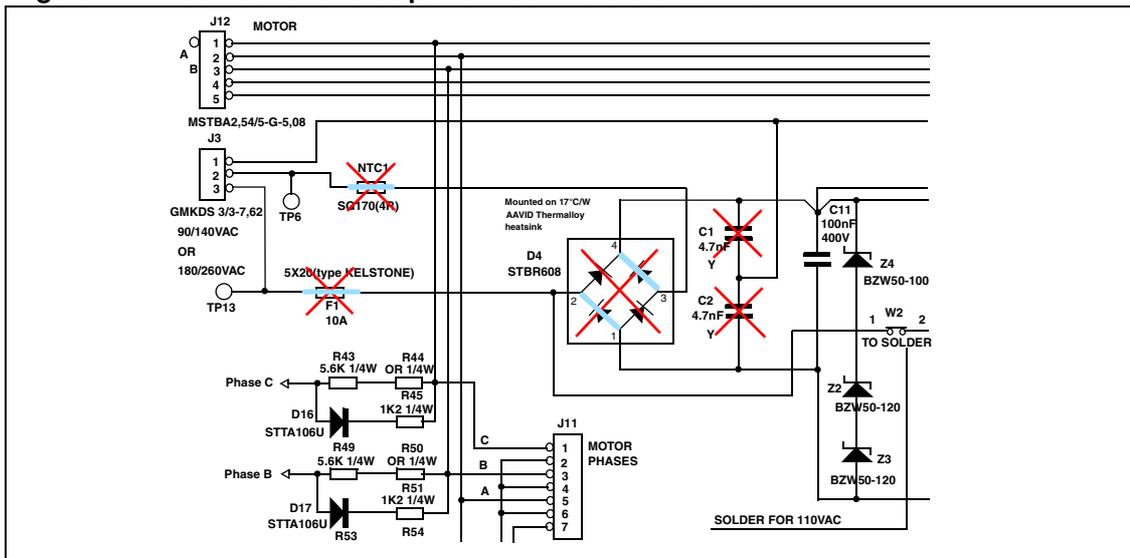
To implement the PFC with the ST7MC starter kit we developed a power board “Add On” that realizes the control of the Bus voltage with a boost topology.

The Power Add On is connected to the mains and provides the Bus voltage for the starter kit. The Power Add On requires two connections with the starter kit. One is the PWM generated by the microcontroller coming from the starter kit and the second sends the zero crossing signals to the starter kit. The Add On power board needs a supplementary 15 Volts to supply the driver, which can be provided by the starter kit (J16). The starter kit is then connected to the motor by the wire for the phases and with the tachometer signal if required.

The Add On power board provides the rectified and controlled voltage bus for the starter kit. The starter kit board has been modified as in [Figure 2](#)

- the bridge D4 has been removed and correctly short-circuited (pin 1-2; pin 3-4)
- the capacitances C1 and C2 have been removed
- the NTC1 has been removed and short-circuited
- the fusible F1 has been removed and short-circuited

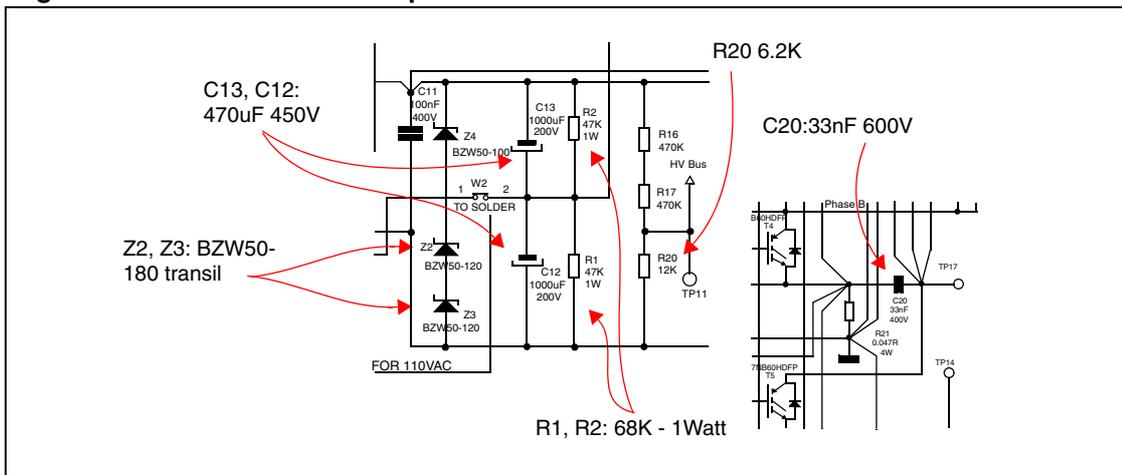
**Figure 2. Modifications to be performed in the Starter Kit**



The modification has been performed also on the value of some component in order to work in safe with a bus voltage of 400-500 Volt. So the following components have been substituted: (see [Figure 3](#))

- C12 and C13 bulk capacitors have been replaced with one of 470uF 450Volt
- The transil Z2 and Z3 has been replaced with BZW50 -180
- R1 and R2 resistors have been replaced with 68K - 1W
- C20 capacitor has been replaced with 33nF - 600V

**Figure 3. Modifications to be performed in the Starter Kit**



To get the Bus voltage value a voltage divider with R16-R17 and R20 is used. To get 5 Volts as a maximum voltage for the AD converter with the new Bus voltage max value, R20 must be replaced with a 6.2K resistance.

To connect the Power Add On board with the starter kit, use two control cables, one to communicate the PWM for the Add on coming from starter kit and one to get the zero crossing from the Add on to the starter kit. The connection of the zero crossing cable is critical. The shunt resistor has been connected near the pin of the starter kit to avoid a capacitive parasite effect of the cable acting as a filter for the zero crossing signal and a capacitor of 12pF has been added to filter the noise.

To generate the PWM for the PFC, the Timer B of the micro is used. The PWM signal of the PFC Power Add On is connected to the OCMP1\_B pin of the micro (J10 Pin 3) and the Zero Crossing signal of the Add On reaches the ICAP1\_B pin of the micro (J10 Pin 7).

The PE2 pin it is connected with ICAP1\_B, because it is used to force the reset of PWM when the ZCD signal is missed.

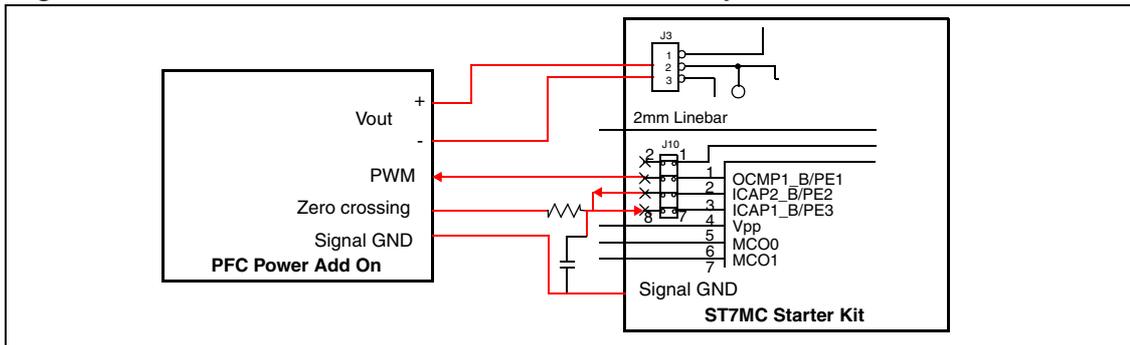
This could happen for example when the instantaneous input voltage is too low to energize the inductor.

The Vout of the Add On is the Mains for the Starter Kit board so must be connected to the Pin 2 and Pin 3 of J3.

The ground signal is connected directly from the ground of the micro to the ground of the driver in the Add On.

The connections are depicted in [Figure 4](#).

Figure 4. Connection between Starter Kit and Add On power board



### 3 Firmware description

#### 3.1 Flowchart

Figure 5 shows the flowchart of the ART interrupt service routine that is called every 1ms.

Figure 5. ART Interrupt service routine for PFC

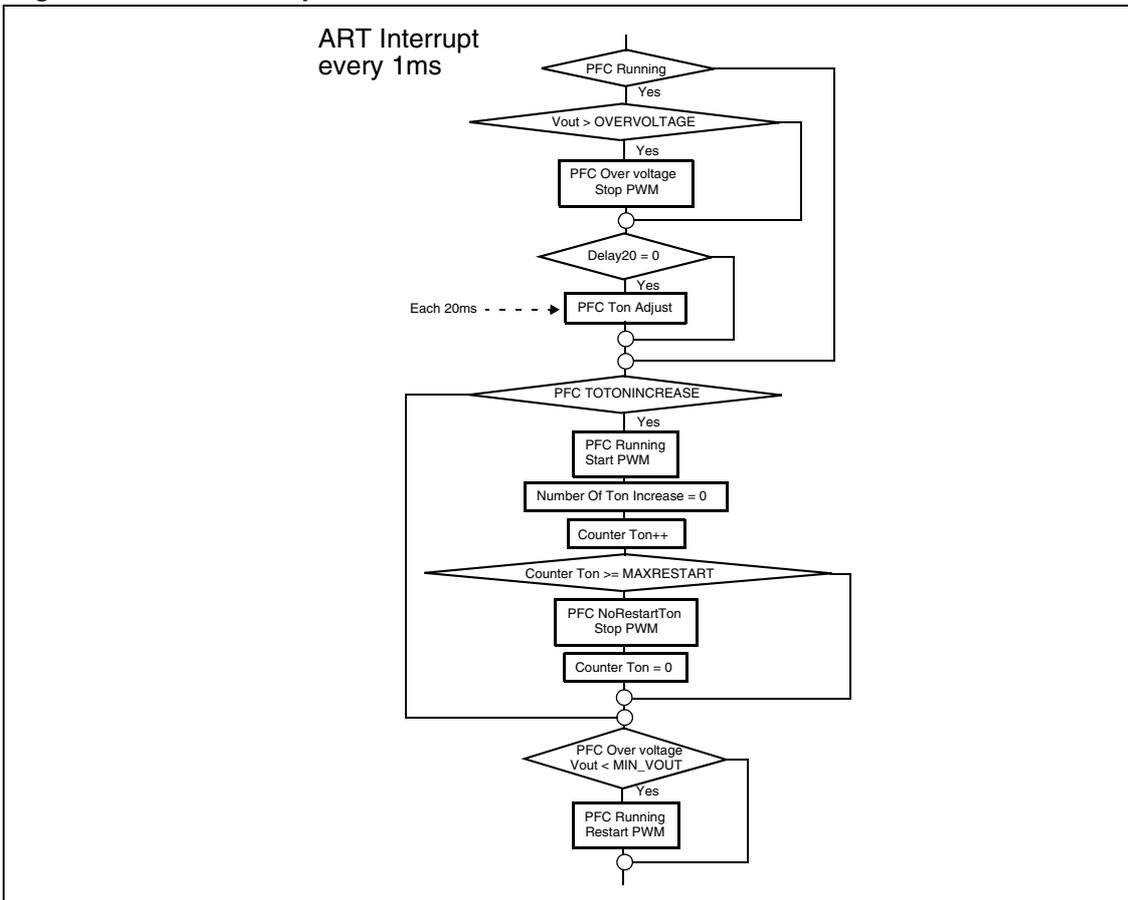


Figure 6 shows the main loop.

Figure 6. Main Flowchart

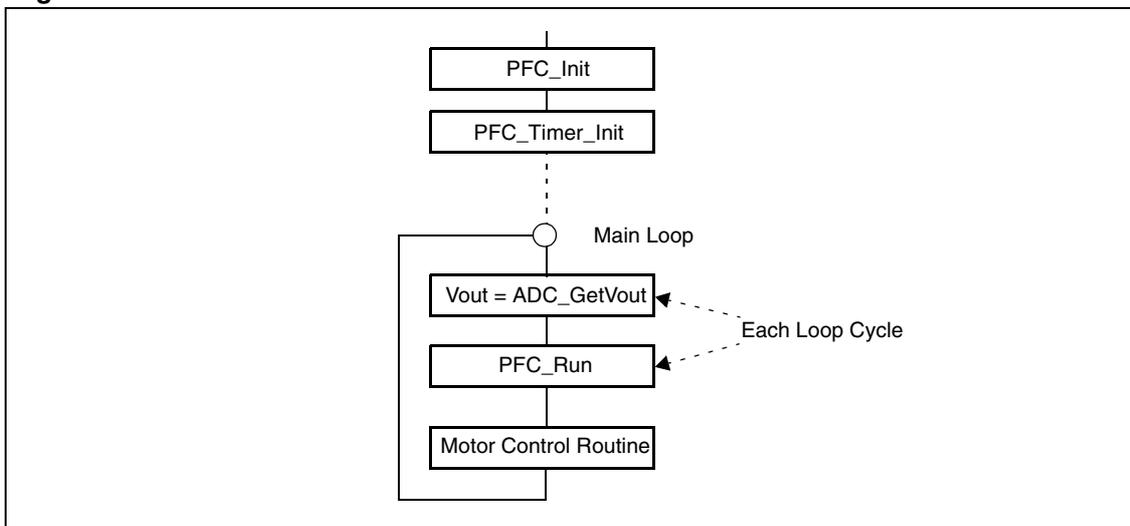


Figure 7 shows the PFC\_RUN function.

Figure 7. PFC\_RUN Flowchart

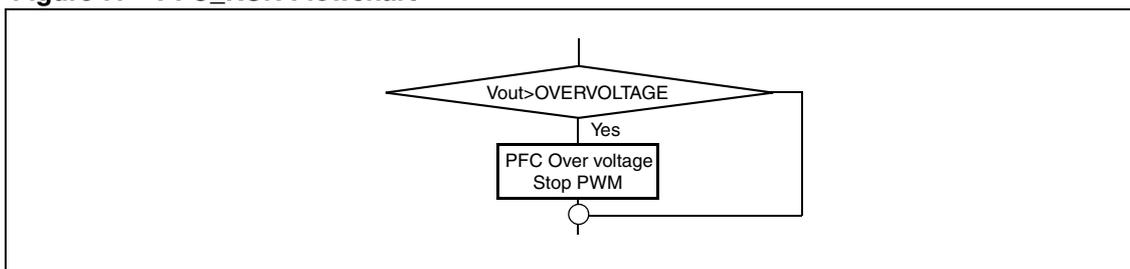
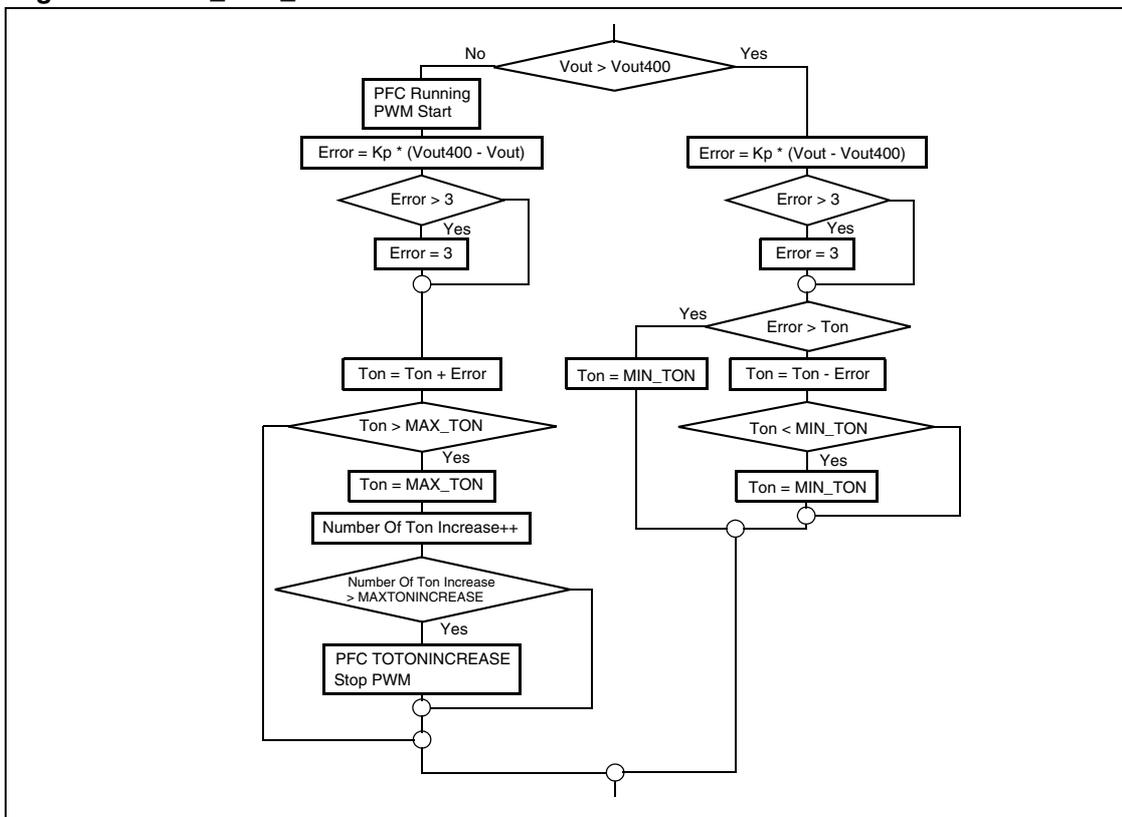


Figure 8 shows the PFC\_TON\_ADJUST routine.

Figure 8. PFC\_TON\_ADJUST



### 3.2 PFC software description

This paragraph contains a description of the part of the software related to the PFC. The complete explanation of the software is beyond this AN. For a more detailed explanation of the motor control software library please refer to the application note AN1904.

The modules related to PFC are the following:

- Pfc.c
- Pwmart.c (Partially)
- Timer.c

The file Pfc.h contains some parameters that can be customized by the user according the application.

At the beginning of the main module (main.c) there is the initialization of the PFC variables and timer parameters.

```

PFC_Init();
PFC_TIMER_Init();
SetBit(TBCR2, TBCR2_OC1E);
    
```

Then in the main loop the only two tasks performed are the acquisition of the Bus voltage Vout

```
Vout=ADC_GetVout();
```

and the check of over-voltage detection condition, performed in the procedure PFC\_Run.

In the Pfc.h file are defined different status of the PFC system:

```
#define PFCOFF 0x00 /* no fault*/
#define TOOTONINCREASE 0x01 /* Too Ton increase*/
#define OVERVOLTAGEFAULT 0x02 /* OverVoltage detect for MAXOVERVOLTAGE time*/
#define PFCRUNNING 0x04
#define LOWVOLTAGEFAULT 0x10 /* Low voltage on DC BUS */
#define NORESTARTTON 0x20 /* No restart after OverVoltage */
#define NORESTARTOV 0x40 /* No restart after OverVoltage */
#define EXTBREAK 0x80 /* External break event */
```

The other PFC routines are called inside the ART interrupt. This is used as a time base for all time-related issues of the motor control routine and it is generated every 1 ms.

The PFC Ton Adjust routine it is called each 20 ART interrupts (20 ms) if the status of the system is PFC Running and this routine is used to calculate and set the new Ton duration.

- If the status of the system is TOOTONINCREASE it means that the PWM is stopped because there was too much successive increase of the Ton caused for example by an overload condition. In this case the software tries to restart the PFC clearing the variable "Number Of Ton Increase" and increasing the variable "Counter Ton". If "Counter Ton" reaches the MAXRESTART value the status will be changed in NORESTARTTON and the PWM will be stopped.
- If the status of the system is OVERVOLTAGE and Vout is below MIN\_VOUT, during the ART interrupt the software restarts the PWM.

### PFC Ton adjust

This routine is dedicated to the control of the Bus voltage by means of the Ton duration variable. It is the only PFC-related routine that requires some CPU load. It is executed every 20ms and its duration is 15 microseconds, so the CPU load is 0.075%.

The Bus voltage is scaled by a factor 0.0065 through a voltage divider. Then the A/D conversion introduces another factor of 255/5 so to convert the Voltage bus value expressed in volts into the value stored inside the software we can use the formula:

$$V_{out} = V_{bus}[\text{Volt}] \times 0.334$$

rounded down to the nearest integer.

So we have the following parameters:

```
#define VBUS 140 // = 0.334 * VBus
#define MIN_VOUT 127
#define OVER_VOLTAGEDC 155 //
```

VBUS: is the target bus voltage.

OVER\_VOLTAGEDC: if the bus voltage exceeds this value the firmware determine an over voltage. In this case it stops the PWM and the PFC\_STATUS will be changed in PFCOVERVOLTAGE.

MIN\_VOUT: if the voltage bus drops under this value after an over voltage, the system restarts the PWM generation and the PFC\_STATUS will be changed in PFCRUNNING.

The error is the difference between the actual value of the voltage bus ( $V_{out}$ ) and the target voltage ( $V_{BUS}$ ) multiplied by a factor of  $K_p$ . The error is subtracted from the actual value of the  $T_{on}$ .

The value of  $T_{on}$  is the number of Timer B steps.

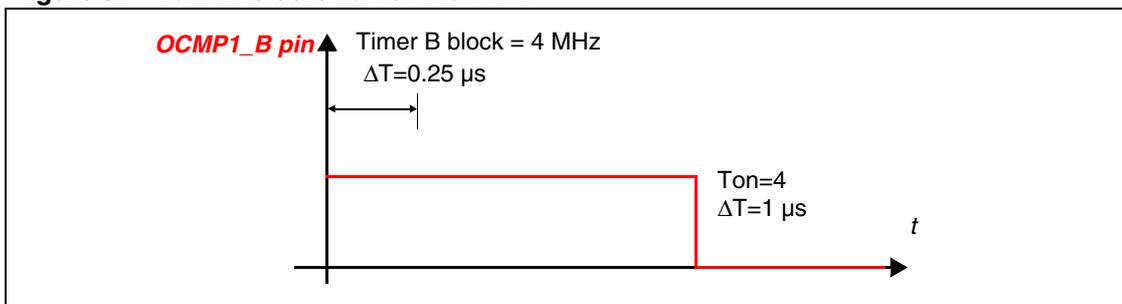
$T_{on}$  is inferiorly limited to  $MIN\_TON$  value and superiorly to  $MAX\_TON$ . If  $T_{on}$  is set to the maximum value the counter "Number Of Ton Increase" is increased by one, if this variable reaches the value  $MAXTONINCREASE$  the system PFC status is changed into  $TOOTONINCREASE$  and the PWM it is stopped.

### Timer.c

Timer.c module is used to setup and control the generation of the PWM control signal. To generate this signal it is used the Timer B peripheral in one pulse mode. The output pin  $OCMP1\_B$  is used as PWM control signal.

The Timer B frequency is fixed to 4 MHz so each step is  $0.25\mu s$ .  $T_{on}$  duration sets the number of steps in which the  $OCMP1\_B$  is in high state (see [Figure 9](#)).

**Figure 9. Ton time duration of the PWM**



$TimB\_init(T_{on})$  is used to set up the Timer B to generate the pulse.  $T_{on}$  sets the number of steps of the timer in which the timer output is high.

$TimB\_start()$  is used to start the timer.

$TimB\_stop()$  is used to stop the timer.

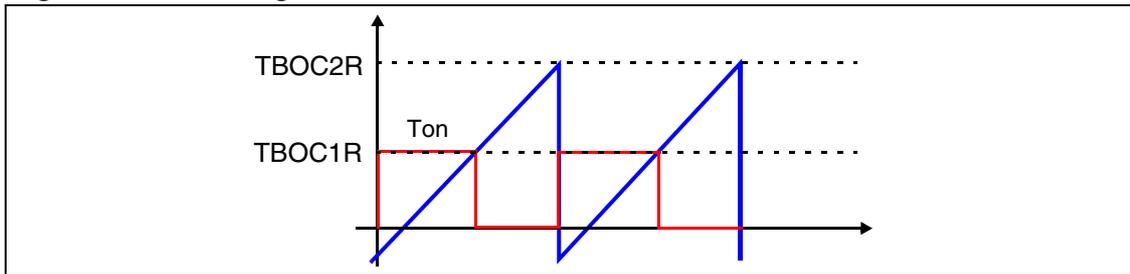
### Vector.c

$TIMB\_Interrupt$  is generated when Timer B reaches the value  $TBOC2R = 0x0F9B$  (After 1 ms the restart of the Timer is forced using  $PE2$ ) this interrupt happens only in the zero current event it is not correctly detected for example when the input voltage it's near the 0V.

At each of this interrupt if the  $T_{on} < MIN\_TON$  the output of the PWM is switched off this to avoid the a too short pulse it's generated on the gate of the mos.

Else if  $T_{on} \geq MIN\_TON$  the  $TBOC1R$  is set to  $(T_{on} - 5)$  to set the pulse of PWM equal to  $T_{on}$  step of timer frequency (4 Mhz)

Figure 10. Restarting the PWM if maximum value is reached before the ZCD



## 4 Hardware description

### 4.1 Power stage

The criteria used for the design of the power stage are extracted from the AN966 “L6561, Enhanced Transition Mode Power Factor Corrector”. The steps followed have been to fix the operating conditions and then to dimension the single part of the design to these.

- Mains voltage range:  $V_{rms}(min)$   $V_{rms}(max)$
- Output voltage:  $V_{out}$
- Output power:  $P_{out}$
- Minimum switching frequency:  $F_{sw}$
- Maximum output voltage ripple:  $\Delta V_{out}$

#### 4.1.1 Power section design

##### Input Bridge

The input diodes bridge can use standard slow recovery, low-cost devices. The quantities to consider will be just the input current ( $I_{rms}$ ), the maximum peak mains voltage and the thermal data of the diodes.

##### Input capacitor

The input high frequency filter capacitor ( $C_{in}$ ) has to attenuate the switching noise due to the high frequency inductor current ripple.

High values of  $C_{in}$  alleviate the burden to the EMI filter but cause the power factor and the harmonic contents of the mains current to worsen, especially at high line and light load. On the other hand, low values of  $C_{in}$  improve power factor and reduce mains current distortion but require heavier EMI filtering and increase power dissipation in the input bridge. It is up to the designer to find the right trade-off in their application.

##### Output capacitor

The output bulk capacitor ( $C_o$ ) selection depends on the DC output voltage, the admitted over voltage, the output power and the desired voltage ripple.

The 100 to 120Hz (twice the mains frequency) voltage ripple ( $\Delta V_{out} = 1/2$  ripple peak-to-peak value) is a function of the capacitor impedance and the peak capacitor current.

$$C_{out} \geq \frac{I_0}{4\pi f \Delta V_{out}} = \frac{P_{out}}{4\pi f V_{out} \Delta V_{out}}$$

##### Boost inductor

Designing the boost inductor involves several parameters and different approaches can be used.

First, the inductance value must be defined. The inductance (L) is usually determined so that the minimum switching frequency is greater than the minimum switching frequency that avoid audible noise, this value it's fixed by software equal to 10kHz to ensure a correct TM operation. Assuming unity PF, it is possible to write:

$$T_{on} = \frac{LI_{Lpk}}{\sqrt{2}V_{I_{rms}}} \quad T_{off} = \frac{LI_{Lpk} \sin(\theta)}{V_{out} - \sqrt{2}V_{I_{rms}} \sin(\theta)}$$

So it is possible to calculate the value of the inductor as a function of the minimum switching frequency.

$$L = \frac{V_{i_{rms}}^2 (V_{out} - \sqrt{2}V_{I_{rms}})}{2F_{SW} P_i V_{out}}$$

## POWERMOSFET

The choice of the MOSFET concerns mainly its  $R_{ds}$ , which depends on the output power, since the breakdown voltage is fixed just by the output voltage, plus the over voltage admitted and a safety margin.

## Boost diode

The boost freewheeling diode will be of a fast recovery type.

Design parameters used in this AN:

- Input voltage: 176V..264V
- Output regulated voltage: 400V
- Output power: 600W
- Minimum switching frequency: 80kHz
- Full load output ripple: 4%

$$I_{rms(max)} = \frac{P_{out}}{V_{in(min)}} = 3.4A$$

- Input Bridge: Generic 10A Bridge
- Input Capacitor: 0.22μF
- Output Capacitor 470μF 450V
- Boost Inductor 80μH with 29 turns 0.40 mm x 10 in the primary saturation current 10A and 3 turns in the secondary
- POWERMOSFET P12NK60
- BOOST DIODE STTA12

To calculate all these values you can follow the formulas used in the AN966.



# 6 Measurement

Figures 12 and 13 show the behavior of the PFC in terms of the Boost Inductor Current, the DC Bus Voltage and the Drain Voltage. The operating conditions are:

- $V_{in} = 220\text{ V Ac}$
- $\text{Load} = 440\text{ W}$

Figure 12. DC bus drain voltage

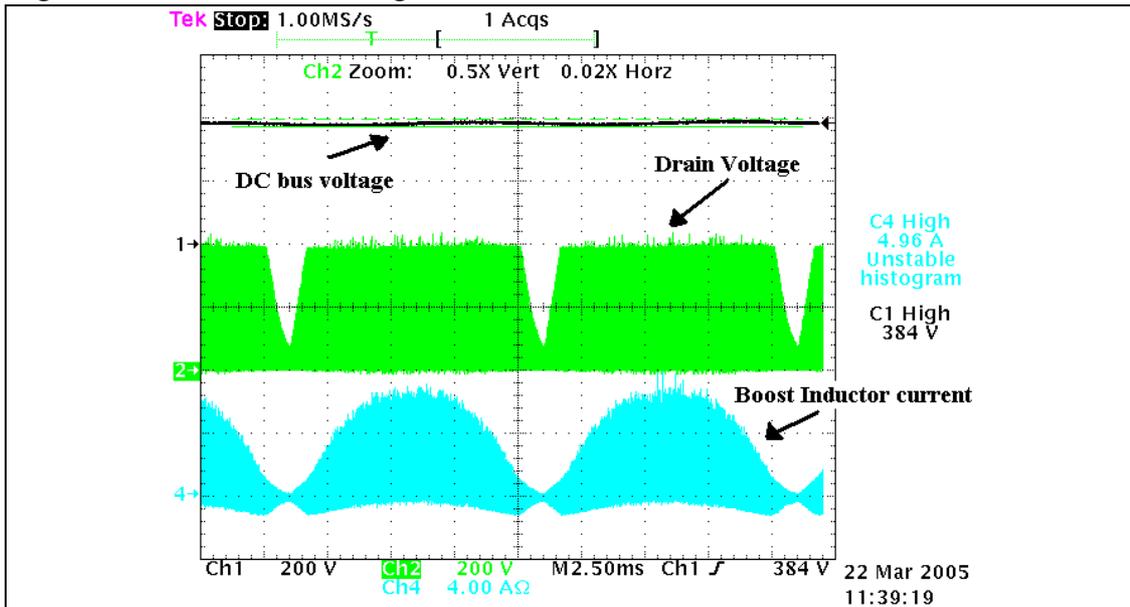
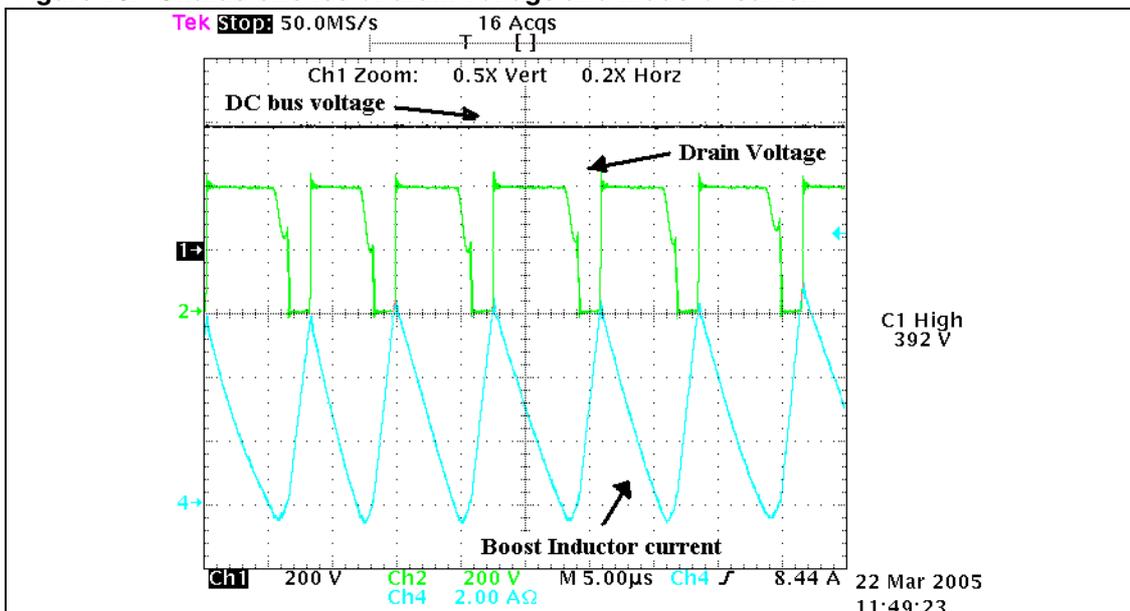


Figure 13. Characteristics of drain voltage and inductor current



## 7 References and related materials

1. ST7MC datasheet
2. TD22x datasheet
3. AN966 L6561, Enhanced Transition Mode Power Factor Corrector
4. AN1904 Software library for AC induction motor
5. ST7 Software Library, <http://www.st.com/mcu>

## 8 Revision history

**Table 1. Document revision history**

<b>Date</b>	<b>Revision</b>	<b>Changes</b>
13-May-2005	1	Initial release
16-Jul-2007	2	Removed references to obsolete products

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